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DESIGN OF AIRCRAFT ELECTRIC POWER SUPPLY SYSTEMS

by

G. D. Vlasov

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FOREWORD

The equipment of a modern aircraft is a series of complexes joined together into a unified system. Their operation is not possible without the use of electrical energy, without the creation of various electrical machines, drives protective and control equipment. In recent times there has been an unprecedented growth of the speed and altitude of flight. This presents scientific and engineering-technical workers with a number of complicated tasks in providing high quality electrical supply with a higher degree of reliability, durability, and stability of operation under all conditions of flight, including emergency conditions.

Alternating current and direct current energy systems are being perfected, work continues on the stabilization of the frequency of a-c generators without the use of constant speed drives, on obtaining electrical energy by means of thermoelectric, electrochemical, and nuclear sources, on increasing the accuracy on the stabilization of parameters and of the efficiency of primary and secondary sources of energy, on increasing the reliability and stability of operation of the energy system at high temperatures and under conditons of supersonic high altitude flight.

This book is an attempt to connect theoretical questions with the practical optimal decisions and recommendations on designing electrical supply systems, on methods of developing and drawing up plans, determining the weight and the reliability criteria, selecting the optimal configurations and protection of this power supply network and the principles of construction of the most reliable primary and secondary a-c and d-c energy systems.

In the book material on primary and secondary energy systems is systematized optimal versions of electrical energy transmission and distribution systems, and types of protection of the electrical network are examined. Also a comparative appraisal and recommendations on the selection of optimal electrical supply systems are given.

The material collected in this book can be used not only by designers in the designing of electrical supply systems but also automation and other equipment specialists taking part in the development of new electrical supply systems.

The author is grateful to N. T. Koroban and candidate of technical science M. A. Yermilov for critical remarks and valuable suggestions given during the review and editing of the book. To Doctor of Technical Sciences V. D. Morozovskoy and Engrs. B. L. Kerber, A. B. Shaposhnikov, N. F. Makokin and E. N. Korshunov for valuable advice given during the review of the manuscript, to the Eng. V. D. Labutin who gave me a great deal of help during the preparation of the manuscript, to Engrs. N. M. Nikitina and L. S. Tavluyekua who did a considerable part of the graphical work. The author requests that all critical remarks about the book be sent to the following address: Moscow, K-51, Terovka, 24, Machine Construction Publishing House.

Section I. Design of Aircraft Electrical Supply Systems

Chapter 1. General Problems of Aircraft Electrification.

1. The Role of Electrical Supply Systems and their Classification.

For supplying power to special equipment aircrafts use different types of energy; hydraulic, pneumatic, mechanical and electrical. Electrical energy is the most universal and widely used in all systems of aircraft equipment.

In Comparison with other types of equipment electrified equipment has a number of important advantages; reliability and durability, minimal vulnerability, small weight in volume, simplicity and convenience in operation.

Electrical energy is easily transmitted over distances, and distributed to separate users. It can be transformed into other types of energy. With its help it is easy to automate a series of operations and thus lessen the work strain of the group so that they can concentrate their attention on solving the principal problems.

Electrification and automation for aircraft systems considerably raises the relative weight of the electrical equipment in comparison with other elements of the aircraft structure. The capacity of the installed electrical energy sources reaches 250 KWt with the extension of the electrical network to over 100 km.

The reliability and precision of the operation of different aircraft systems depends primarily on the reliability, continuity and quality of the electrical supply which is provided for by the primary and secondary d-c and a-c electrical systems.

The constant supply of high quality electrical energy is very important for the control and navigation systems in all flight conditions especially during take-off and landing where even a short-term failure of supply or a lowering of its quality could lead to catastrophy.

To increase the reliability and safety of flight the complete duplication of control and navigation systems has appeared necessary. This problem could be solved by the use of separate power supply channels for the duplicated systems with a parallel operation of the energy sources. During take-off and landing it is advisable to conduct the power supply at the duplicated channels from two autonomous systems. This will guarantee continuity and high quality of the power supply by one oi .he channels for the vital systems with the failure of any power supply channel.

To provide independence for the electrical power supply system during take-off and landing it is necessary to separate the primary and secondary energy systems into groups (not less than 2) with parallel operation of the sources for each group. Then the failure of the separate sources or sections of the network of one channel will not influence the normal operation of the others.

As a result of the diversity of models, functions, and conditions of operation of aircraft it is impossible to create a unified optimal electrical supply system. Therefore the choice of a rational electrical supply system is determined by the specific model and function of the aircraft.

In all cases (independent of the model and function of the aircraft) the electrical supply system consists of the primary (basic) and the corresponding complex of secondary (auxiliary) energy systems. The entire energy system is designated according to the type of the primary energy system.

The primary energy system obtains electrical energy from the primary sources and provides direct power supply to the overwhelming majority of the users.

The basic sources of energy are generators driven directly from the aircraft engine or through constant speed drive. For the auxiliary systems the source is a storage device or a generator driven by an independent engine or turbine driven by the airstream.

The primary energy systems are classified by the type of current and frequency in the three basic types.

1. Direct current energy systems.

2. Energy systems with a three phase alternating current and a speed frequency.

3. Energy systems with a three phase alternating current and a constant frequency.

The secondary energy systems obtain electrical energy from secondary sources converted to the voltage frequency and type of current of the primary energy system. They then provide power supply into users.

Their energy sources are rotating or static convertors or inverters, depending on the type of primary energy systems. If the frequency of the primary and secondary a-c energy systems coincide then the voltage is converted by transformers.

Secondary energy systems are classified into four basic types according to the type of current and the frequency.

1. Energy systems with a single-phase alternating current in the constant frequency.

2. Energy systems with a three-phase alternating current and a constant frequency.

3. Energy systems with a three-phase alternating current and a precision frequency.

4. Direct current energy systems.

The basic parameters of primary and secondary energy systems are given in Table 1.1.

In addition to those shown in Table 1.1 in some cases d-c 112 v and single-phase a-c 200 and 115 v energy systems are used. Secondary energy systems with single phase a-c, 47 and 12 v, with constant and sweep frequency are also used.

Table 1.1: Basic Primary and Secondary Energy Systems

	Системы	Тип энергосистемы	Напряжение источника энергии *в*	Напряжение на клеммах потребителя *в*	Частота *гц*	Примечание
2	Первичные	Постоянного тока напряжением 27 *в*	28,5±3%. Допускается 28,5±4% 28,5±7%	27±10%. Допускается при аварийном режиме 20 *в*	—	U=28,5±2% с точным регулированием. Пульсации 8 %
3	Первичные	Трехфазного переменного тока напряжением 200/115 *в* переменной частоты	208/120±3% 208±3%	200/115±5% 200±5%	300—900	f=400±5% *гц*, если привод от турбовинтового двигателя
4	Первичные	Трехфазного переменного тока напряжением 200/115 *в* постоянной частоты	208/120±2% 208±2%	200/115±5% 200±5%	400±1%. Допускается 400±2%	U=208±(0,1–1)% с точным регулированием
5	Вторичные	Однофазного переменного тока напряжением 115 *в* постоянной частоты	115±3%	115±5%	400±5%	На некоторых преобразователях $f=400^{+7}_{-5}$% *гц*
6	Вторичные	Трехфазного переменного тока напряжением 36 *в* постоянной частоты	36±3%. Допускается 37±3%	36±5%	100±2%	В специальных преобразователях f=100±1% или 100±0,1% *гц*.
7	Вторичные	Трехфазного переменного тока напряжением 36 *в* прецизионной частоты	36±3%	36±5%	100±0,05%	Применяются также частоты 500, 800, 1000, 1200, 2000, 1000 и 10 000 *гц*
8	Вторичные	Постоянного тока напряжением 27 *в*	$28,5^{+3}_{-9}$%	27±10%	—	Пульсации напряжения 8%

Row 1 (header row) is marked "1" in the margin.

1. Systems, Type of Energy System, Voltage of the Energy Source, volts - v, Voltage at the terminal of the user, volts - v, Frequency cps, Comments.

2. Primary, Direct current 27 v, 28.5 ± 3% tolerance 28.5 ± 4% 28.5 ± 7%, 27 ± 10% tolerance during emergency conditions 20 v, - , U = 28.5 ± 2% with precise control, capital fluctuation 8%.

3. Primary, Three-phase a-c 200/115 v sweep frequency, 208/120 ± 3% 208 ± 3%, 200/115 ± 5% 200 ± 5%, 300-900, f = ∿ 400 ± 5% cps, driven from a turbo prop engine.

4. Primary, Three-phase a-c 200/115 v constant frequency, 208/120 ± 2% 208 ± 2%, 200/115 ± 5% 200 ± 5%, 400 ± 1% tolerance 400 ± 2%, U = 208 ± (0.1-1) % with precise control.

5. Secondary, Single-phase a-c 115 v constant frequency, 115 ± 3%, 115 ± 5%, 400 ± 5%, on some convertors f = ∿ 400^{+7}_{-5} % cps.

6. Secondary, Three-phase a-c 36 v constant frequency, 36 ± 3% tolerance 37 ± 3%, 36 ± 5%, 400 ± 2%, on special convertors f = 400 ± 1% or 400 ± 0.1% cps.

7. Secondary, Three-phase a-c 36 v precision frequency, 36 ± 3%, 36 ± 5%, 400 ± 0.05 %, also used are 500, 800, 1000, 1200, 2000, 4000, and 10,000 cps frequencies.

8. D-c 27 v, 28.5^{+5}_{-9} %, 27 ± 10%, -, voltage fluctuation 8%.

2. Short Historical Sketch of the Development of Electrical Supply Systems in Aircraft.

The history of the development of aircraft electrification covers a relatively small period of time, and is closely connected with the progress in aviation technology and electrical technology.

In 1869, A. N. Ladygin designed the world's first heavier than air craft with an electrical engine the "electroted". The power supply for the electric engines was supposed to be from special storage systems developed by P. N. Yablochkov.

In 1912, the first bombers where electricity was used for ignition, heating, and radio-communication were constructed in Russia. They were the"Russian Hero", "Il'ya Muroneds" and "Svyabogor". The sources of energy were a-c 0.5-2 kVa generators driven from the aircraft engine or from a windmill.

The first airplanes had 600-1000 cps a-c electrical supply systems since the basic users - spark radio telegraph stations, required a-c while for lighting and heating the nature of the current did not matter.

In 1919 aviation switched over to a systems 8 v d-c electrical supply sources of energy of which were storage systems and wind-driven generators with a capacity of 36 v. The voltage of the network was increased in 1923 to 12 v and in 1930 to 24 v and remained at that until 1939.

Until 1929 wind-driven d-c generators with a capacity of not exceeding 250 W were used.

In 1934 generators driven from the main aircraft engine appeared, the capacity in 1936 was 500 W, and in 1939 - 1000 W.

In 1934 on the airplane "Maxim Gorky" three-phase a-c 120 v and 27 v d-c were widely used for the first time. The sources of energy were two three-phase a-c generators with a capacity of 3 - 5.5 kVa and a voltage of 120 v and two d-c generators with a capacity of 3 - 5.8 kW and a voltage of 27 v, these generators were driven by two special internal combustion engines. The great turning point in the development of the electrification of aircraft was a creation in 1939 of the Be-2 dive bomber on which for the first time electrical mechanisms on the landing gear, the stabilizer, flaps, control of the radiator, trimming caps, and other equipment, were widely used. These users were supplied with 27 v d-c from two generators with a capacity of 1 kW each.

Beginning in 1939 the quantity and capacity of the using units continually increases the length of the electrical network and the character of the users changed relative to the type of current, voltage and frequency used. The production, transmission, and distribution of electrical energy became considerably more complicated. Electrical supply systems changed and their role grew. electrical energy has become the most important type of power supply for the complex assemblies of aircraft equipment.

Since 1939 there has been an intensive development of 27 v d-c primary energy systems. The basic sources of energy of which are d-c generators driven from the aircraft engine and storage batteries as reserve sources.

During this period the capacity of generators has increased from 1 to 18 kW, and a number of generators on an aircraft has increased from 1-2 to 8-12 generators. The installed capacity of the energy system grew from 100 to 200 times, reaching the maximum in the middle of the 1950s. At the same time there have been changes in the system of distribution of electrical energy (centralized, decentralized, and mixed), the configuration (open and closed) and the protection of the power supply network.

During the middle of the 1950s the speed in altitude of flight grew, this necessitated a qualitative change in the source of the energy, equipment, and the power supply network. Non-contact generators, intensive cohesion, static voltage regulators, and perfected systems of protection from inverse current, over-voltage, short circuits, and other kinds of damage appeared. Annular multichannel power supply network equipped with double relay and having higher reliability became widespread.

For the power supply of a series of instruments, transmitters, radio and radio-locating equipment, and other equipment, d-c with increased voltage and a-c with constant frequency were needed. The power supply for secondary systems developed parallel to the d-c primary systems. The source of energy for these systems was a rotating dynamotor, a single-phase 115 v 400 cps convertor with a capacity from 100 to 600 v-amperes, and a three-phase 36 v 400 cps convertor with a capacity from 70 to 3000 v-amperes. In recent times static convertors have become widely used.

Energy systems with a separate operation for convertors have found practical use. In the initial period (until the 1950s) convertors were used as individual power supply sources for separate users. Consequently as both the quantity and capacity of the sources and users grew convertors were used for the group power supply of the users.

Together with the increased capacity of the users and the necessity to increase their reliability and lower the weight of electrical equipment, in the 1950s began an intensive development of a-c, 200/115 v sweep and constant frequency for 400 cps primary energy systems. Generators with a capacity from 7.5 to 120 kVA appeared. The installed capacity of aircraft energy systems reached 250 kW.

In the initial period single-phase sweep frequency energy systems were developed and were used for auxiliary purposes (heating, surface equipment, and others) on aircraft with a basic d-c energy system. In recent times three-phase d-c energy systems are widely used as a basic primary energy system. They have constant speed drive, non-contact generators and static elements for control and protection.

To provide power supply for the d-c users along with the three-phase a-c primary energy systems small capacity d-c 27 v secondary energy systems developed. They used static sources of energy which converted a-c into d-c.

At the present time energy supply systems have developed in two directions; a primary 27 v d-c energy system, and a three-phase a-c 200/115 v primary energy system, one or the other is used depending on the model and function of the aircraft.

3. Conditions of Operation of Electrical Supply Systems.

Aircraft electrical supply systems operate under conditions significantly different from those on the ground. Their altitude and speed of flight, acceleration, and the various attitudes of the aircraft have an effect on their operation. The altitude is characterized by the parameters of the surrounding air; temperature, density, pressure, humidity, chemical composition, dielectric strength, specific heat, and other factors.

Within the limits of the troposphere (up to 11 km) temperature of the air decreases evenly with the increase in altitude, then remains constant (from an altitude of 11 km to 30 km) at about - 56.5° C, as one rises further the temperature reaches 0°C at an altitude of 40 km.

The pressure and density decreases with an increase in altitude. The amount of moisture and oxygen are also reduced. At the same time the concentration of ozone increases.

The relative humidity of the air can reach 98% with a temperature of the surrounding air at + 20° C.

With the lowering of the pressure the dielectric strength of the air decreases. At a height of 15 km the dielectric strength is lowered to 2.5 times. A result of this is that the duration of arcing increases. The change of the parameters of the surrounding air have a negative effect on the operation of electrical systems. From this the effectiveness of cool in this lower (especially in the stratosphere) altitude, the commutation conditions for electrical machines deteriorates, the degree of sparking and wear of the brushes increases, the starting time of the mechanisms increases as a result of a thickening of the lubricants, the operation of commutation devices deteriorates in connection with the growing ionization and air conductivity the brittleness of insulation materials increases, the efficiency of electrolytic capacitors and storage batteries deteriorates as a result of the increase of their internal resistance or the freezing of the electrolytes.

As the speed of light increases it raises the temperature of the surface layer and the air frame of the aircraft, this leads to a deterioration of the cooling conditions, an increase in corrosion, a lowering of mechanical strengthening, the deterioration of the properties of the insulating materials and to other results.

Within wide limits the change in temperature leads to a change in the resistance of coil winding, eleastic quality of springs and of linear dimensions. These effects cause changes in the adjustment of the equipment.

Mechanical over-loading (vibration, bumps, shocks, dynamic forces) has an important influence on the operation and endurance of the electrical equipment.

The frequency and amplitude of the vibrations are determined by the model of aircraft and the primary engine. The frequency of the vibrations usually fluctuates from 0.5 to 500 cps and acceleration reaches 10 G or more. Aircraft and all the electrical equipment found on them can assume any position. This has an effect on the construction of the electrical system and causes additional difficulty in the design of the equipment and its components in the corresponding sections.

4. Basic Technical Requirements of Aircraft Electrical Supply Systems.

The technical requirements of aircraft electrical supply systems are the basic material in design, insulation and operation.

The importance and complexity of the functions carried out by electrical supply systems and their particular conditions of operation call for very stringent requirements.

The basic requirements are as follows:

1. Reliable and failure .ree operation of the system under any flight conditions.

2. High durability and resistance to damage, and the durability of the system to operate after being damaged.

3. Autonomy - the capability of the system to start and to maintain normal operation without an outside source of energy under pre-flight and flight conditions.

4. Minimal flight weight and size with a maximum possible efficiency during flight operation. The lowering of efficiency leads to additional expenditures of fuel, increasing the weight and capacity of the main engine, and consequently increasing the weight of the entire aircraft.

5. High-quality electric energy, i.e., constant voltage and frequency. Divergency from these parameters beyond permissible limits leads to disturbance of normal operation of the units using electricity or to their failure.

6. Safety and operation of servicing - the use of low voltage on the control circuits of aircraft being flown by instrument, the use of hermetically sealed commutation and protective equipment, (especially for systems located close to fuel, oil, and oxygen), the use of better insulating materials in the construction of assemblies, distributors and other equipment.

7. Simple and convenient assembling insulation service and replacement of elements and assemblies in the process of production and operation.

8. High mechanical durability, primarily resistance to vibrations. Elements have to withstand vibration and overloading without suffering damage for the entire course of their service life. Also they should not display sympathetic vibrations within the range of frequencies found on aircraft.

9. High resistance to chemicals. Insulation and other covering elements should be resistant to damage from the effects of moisture, seawater, gasoline, and kerosene, oil and other corrosive mixtures.

10. High electrical and thermal durability.

11. Fire safety. Measures should be taken to prevent the possibility of fires. And fire resistant materials should be used.

12. Safety from explosions. There should be a possibility of localizing explosions in an interior assembly without any harmful consequences for elements nearby.

13. Rapid preparedness for action.

14. Absence of obstacles to the operation of radio equipment, magnetic compasses, instruments, polarized relays, and other equipment arising as a result of the fluctation of voltage at the computator of the generators, and the rectifier outlets, vibrating contacts, and also of a result of magnetic fields created by the different assemblies and drives of the electrical supply system.

The elements of the system should not interfere with one another.

15. The separate assemblies and parts should be inter-replaceable and standardized.

16. A long service life with a minimum cost of production, operation, and repair.

Certain of the requirements listed might have to be given up because they are contradictory. During planning we should find a compromise solution using the most important of them in a particular situation.

Requirements inherent only in definite elements or systems are discussed in the corresponding sections.

Chapter 2. Method of Design of Aircraft Electrical Systems.

1. The Lay-Out of Electrical Equipment According to its Function and Section.

In the process of design, laboratory research, construction, testing and operation of aircraft electrical supply systems, their method of development and formation of plans is important. An efficient method provides for the simplification of the process of designing, designing, completing plans, initiation and control of the basic parameters, broadening the area of work, shortening the time and cost and raising the quality of the completed work at all stages of design, construction and operation of the aircraft. The use of well developed methods allows us to lower the requirements of the qualifications of the designers.

The process of designing aircraft electrical systems is elaborated in the following plan:

1. Main electrical diagram.
2. Semi-assembled electrical diagram.
3. Assembled electrical diagram.
4. Transmission line electrical diagram.
5. Construction sketches.

It is efficient to use the principle of laying out all electrical equipment by sections and functions as the basis of the system* of completing plans as shown in Table 2.1

Table 2.1. Layout of Electrical Equipment by Function .

No.	Index	Designation	No.	Index	Designation
1	E	D-c energy system	9	AP	Automatic pilot
2	EP	A-c energy system	10	L	Lighting
3	AB	Armament (bomb)	11	S	Signals
4	AG	Armament (gun, rocket)	12	F	Photographic Equipment
5	E	Eninge systems	13	R	Radio Equipment (Power Supply)
6	AS	Aircraft steering	14	S	Service Equipment
7	H	Heating system	15	F	Fuel System
8	I	Instruments	16	F	Fire Proofing System
			17	ES	Engine Starting
			18	LG	Landing Gear

Each function includes one or several electrical systems designated to perform a definite operation in the carrying out of that function.

The main electrical diagrams are completed separately for each function with connections between the different functions indicated, if there are any such connections. Thus, this eliminates the necessity of composing general diagrams for the entire aircraft.

Depending on the model of aircraft certain functions might be lacking. In this case their number remains empty and the number of the remaining functions in accordance with the given lay-out is preserved. With the appearance of new functions the sequence of numbering continues. The number of the specific functions should be kept

* Developed by the author in 1950-1953.

for all models of aircraft.

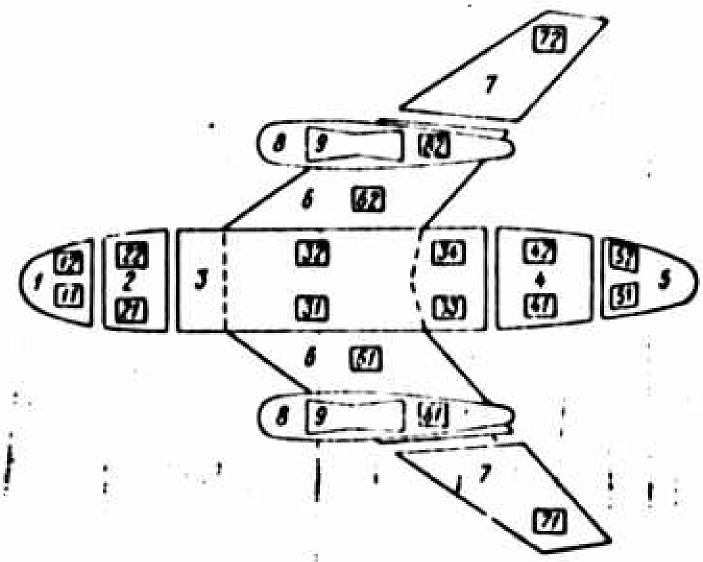


Fig. 2.1. Diagram of enumeration of aircraft sections and panels.

Each function also has a letter index, consisting of the first letter of its name. For example E - energy systems, d-c; I - instruments; P - photographic equipment, etc.

The functional principle of the lay-out of electrical equipment is the basis of the construction and numeration of the principal electrical diagram, assemblies, equipment, and wires.

For construction, technological, and operational considerations the aircraft is divided into several sections; 1 - pilot's compartment; 2 - navigator's compartment; 3 - center section; 4 - technical section; 5 - tail section; 6 - inner wing; 7 - wing; 8 - engine gondola; 9 - engine.

Panels, instrument panels, distributors, and flaps of the aircraft are given a number in which the first digit shows the number of the section, the second the sequential number of the panel in that section. For example the numbers of the panels in the pilot's compartment run from 11 to 19. Panels on the left of the main axis of the aircraft have odd numbers, and on the right, even numbers.

A diagram of the electrical equipment lay-out by section and panel is given in fig. 2.1.

The lay-out of the aircraft by section and enumeration of the panels of the corresponding section is the basis of the numeration of the semi-assembled and the assembled diagrams, bunched conductors, plugs, and enumeration of the blueprints of the constructed units.

2. The System of Numeration of the Main Electrical Diagrams of Assemblies and Wiring.

The functional designation is a basis of enumeration of the main electrical diagrams.

The first two digits designate the number of the group. In accordance with the normal NAP, the electrical equipment group has number 72. The second two digits designate the number of the sub-group.

The principal electrical diagrams are given sub-group 00.

In the numeration of the main electrical diagrams the digits after the dash show the sequential number of the function, for example:

7200-1, - is the main diagram of the d-c electrical system.

7200-2, - is the main diagram of the a-c electrical system.

The numeration of the electrical diagram for the transmission lines is determined by the designation of the transmission line and coincides with the number of the corresponding main diagram. But since the main-function diagram consists of several transmission lines, there is an additional index, giving the sequential number of the transmission line in the main diagram. For example:

7200-1-1, - is the transmission line diagram of the d-c generator.

7200-1-2, - is the transmission line diagram of the storage system. Other systems have similar designations.

The numeration of the load charge is given by function in accordance with the type of current:

7200-21, - is the charge of the d-c load.

7200-22, - is the charge of the a-c load.

The numeration of the electrical systems calculation is given by function in accordance with the type of current:

7200-31, - is the calculation for the d-c electrical system.
7200-32, - is the calculation for the a-c electrical system.

The numeration of the electrical assemblies and equipment is done according to function and following the enumeration of the main electrical diagrams. The first digit shows the number of the function and the second digit the sequential number of the assembly in the given function. Assemblies on the left of an aircraft axis have odd numbers, those on the right have even numbers, for example:

101, - is the left d-c generator.
1402, - is the right boiler, etc., for other equipment.

Each function has its definite integral of numbers. For example from 100 to 199 are the assemblies of the d-c electrical system.

If a hundred number integral is not sufficient then additional numbers are used in the same integral with a zero in front, for example: 0125.

Assemblies installed in a section or a panel have before the number of the assembly the number of the corresponding section or panel. For example, 9-101 is the left d-c generator installed on the engine; 22-118, is the circuit closer of the right generator installed on the navigator's distributor. The number of a section or panel can be written under the number of the assembly. For example: $\frac{101}{9}$, $\frac{118}{22}$, and so on. The number of the assembly is drawn on the blueprint and also on the aircraft in a convenient place.

The above description of the system of enumeration of electrical systems is simple, graphic, easily remembered, convenient for designing, assembling, and operation.

Wires are marked with letter and number indexes in which the first letter designates the function.

For example; L - is lighting; S - Signals, and so on for other functions.

The second letter and sometimes the third, designates the assembly in the function. The number index after the letter shows the sequential number of the wires in the given assembly. For example: EG 1, - is the left generator wire.

Wires of the assembly on the left axis of the aircraft or in front if the assembly is given on the right axis of the aircraft are given odd numbers.

Wires on the right of the axis are closer to the tail if the assembly is on the axis, are given even numbers. The number index remains unchanged from assembly to assembly, including the case when a longer wing for the wires there are terminals or plug and socket connectors.

Wires entering or going out of an assembly should have different number indices. This holds for all commutation equipment, (breakers, switches, buttons, and so on).

With the connection of a wire to the plug socket connector the number of the wire should correspond to the number of plug, as shown in fig. 2.2.

If in this function, one feeder supplies consumers of various types, the letter index after the circuit breaker of the corresponding consumer may be changed.

The basis of marking negative wires is the number of the assembly and the letter M; for example: M592 - is the negative wire of assembly #592.

If during assembly the negative wires are hooked up to a $\pm$, then the marking shown is maintained.

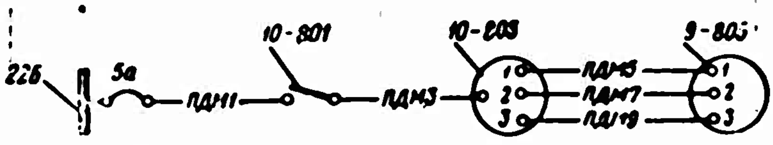


Fig. 2.2. Diagram with a connection of wires to assemblies.

The wires going out of minus-busses into a unit are marked MO general unit. A marked minus wire is shown in fig. 2.3.

If a box has several negative busses and each one has a minus-wire going out of it, then to the index "MO" a number is added; for example, MO 1; MO 2, and so on.

The entire system of numeration for main diagrams, assemblies, wires, transmission line diagrams, load charge, and wire calculations, is shown in Table 2.2.

If a given function has power supply for several users, from one transmission line, then the letter index is changed after the circuit closer of that user.

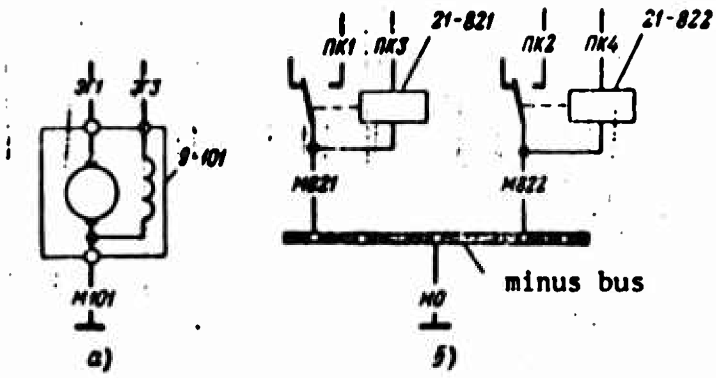


Fig. 2.3. The marking of minus-wires; a - assembly, b - general.

3. System of Enumeration of Arcing Wiring Diagrams, Wiring Diagrams, and Design Blueprints.

The numeration of partial and complete wiring diagrams and the structure of blueprints is based on the division of aircraft into sectors. The first two digits signify the numer of the group. The electrical equipment group is assigned a number "72". The first two digits signify the number of the subgroup.

Partial Wiring Diagrams are assigned the number of sub-group "00". The number of the sector is marked with the second digit after the dash. The first digit "1" after the dash is the conventional index of the partial wiring diagrams, for example:

7200-110 - is the partial wiring diagram of the electrical equipment of the pilot's cabin.

Wire Specifications are formed in accordance with the partial wiring diagrams. The conventional index for the specifications of the wires is the first figure "3" after the dash. For example:

7200-310 - is the specification of the wires in the pilot's cockpit;
7200-320 - is the specification of the wires of the navigator's cabin, and so forth.

Photographic Diagrams are partial wiring diagrams of the control panels, made on photosensitive paper and placed directly in the apparatus in places convenient for observation.

The photographic diagram numeration is based on the numeration of the control panels.

The first digit "1" after the dash is the conventional index pertaining to the partial wiring diagrams. The second and third digits correspond to the number of the control panel, for example:

7200-121 - is the photographic diagram of the left distributing device of the navigator;
7200-182 - is the photographic diagram of the distributing device of the right-hand section of the engine-nozzle.

Bunches of conductors are assigned the letter-digit indices, in which the letters indicate the name of the section, and the digits the cardinal number of the bunch in this compartment. Bunches of conductors, passing from one compartment into another without connection of the places where the compartments join one another, have a two letter, corresponding to the names of the compartments. The bunches of conductors located to the left of the aircraft axis, are assigned odd numbers and those located to the right even numbers, for example:

L 1 - is the left bunch of the pilot's cockpit;
LN 2 - is the right bunch of the flyer-navigator cabin, and so forth.

The number of the bunch is painted with a special paint on the insulation pipes which are set up on the bunch along its length in several places, convenient for observation.

The connecting plugs are assigned double digital indices, in which the digits before the dash indicate the number of the compartment of control panel, and the digits after the dash indicate the cardinal number of the plug in this compartment or panel.

For example: 1-3 is the left plug # 3 of the pilot's cockpit; a diagram of the conductor-bunch enumeration and their connecting plugs is given in fig. 2.4.

The Wiring Diagrams and Structural Installations are assigned a subgroup, corresponding to the number of the compartment (third digit) and the Design Diagrams of the Panels are assigned a subgroup corresponding to the number of the panel (third and fourth digits).

The conventional index for the wiring diagrams and the structural blueprints of the panels is the figure "0" after the dash.

Table 2.2:

A № функции	B Наименование функции	C № принципиальных схем	D Номера агрегатов: E основные	F дополнительные	G Индексы проводов	H № фидерных схем	I № графиков нагрузок	J № расчетов
1	Принципиальная схема энергосистемы постоянного тока	7200-1	100÷199	0100÷0199	Э E	7200-1-1 7200-1-2	7200-21	7200-31
2	Принципиальная схема энергосистемы переменного тока	7200-2	200÷299	0200÷0299	ЭП A	7200-2-1 7200-2-2	7200-22	7200-32
3	Принципиальная схема бомбового вооружения	7200-3	300÷399	0300÷0399	ВБ BA	7200-3-1 7200-3-2		
4	Принципиальная схема стрелкового вооружения	7200-4	400÷499	0400÷0499	ВС FA	7200-4-1 7200-4-2		
5	Принципиальная схема двигательных систем	7200-5	500÷599	0500÷0599	Д M	7200-5-1		
6	Принципиальная схема управления самолетов	7200-6	600÷699	0600÷0699	C У	7200-6-1 7200-6-2		
7	Принципиальная схема тепловых систем	7200-7	700÷799	0700÷0799	Т H	7200-7-1 7200-7-2		
8	Принципиальная схема приборов	7200-8	800÷899	0800÷0899	П I	7200-8-1 7200-8-2		
9	Принципиальная схема автоматических систем (автопилот)	7200-9	900÷999	0900÷0999	А AP	7200-9-1 7200-9-2		
10	Принципиальная схема освещения	7200-10	1000÷1099	01000÷01099	О L	7200-10-1 7200-10-2		
11	Принципиальная схема сигнализации	7200-11	1100÷1199	01100÷01199	С S	7200-11-1 7200-11-2		
12	Принципиальная схема фотооборудования	7200-12	1200÷1299	01200÷01299	Ф Ph	7200-12-1 7200-12-2		
13	Принципиальная схема питания радиооборудования	7200-13	1300÷1399	01300÷01399	Р R	7200-13-1 7200-13-2		
14	Принципиальная схема бытового оборудования	7200-14	1400÷1499	01400÷01499	Б	7200-14-1 7200-14-2		

A № функции	B Наименование функции	C № принципиальных схем	D Номер агрегатов E основные	F дополнительные	G Индекс проводов	H № фидерных схем	I № графиков нагрузок	J № расчетов
15	Принципиальная схема топливной системы (горючее)	7200-15	1500 – 1599	01500 – 01599	Г F	7200-15-1		
16	Принципиальная схема противопожарной системы (нейтрализация)	7200-16	1600 – 1699	01600 – 01699	Н FF	7200-16-1		
17	Принципиальная схема запуска	7200-17	1700 – 1799	01700 – 01799	З St	7200-17-1		
18	Принципиальная схема шасси	7200-18	1800 – 1899	01600 – 01699	Ш Ch	7200-18-1		

A - Number of function, B - name of function, C - number of simplified diagrams, D - number of assemblies, E - main, F - auxiliary, G - wire indexes, H - number of feeder systems, I - number of load schedules, J - number of calculations.

1. Simplified diagram of d-c power system
2. Simplified diagram of the a-c power system
3. Simplified diagram of bombing armament
4. Simplified diagram of firing armament
5. Simplified diagram of the motor systems
6. Simplified diagram of aircraft control
7. Simplified diagram of heating systems
8. Simplified diagram of instruments
9. Simplified diagram of automatic systems (automatic pilot)
10. Simplified diagram of synchronization
11.
12. Simplified diagram of photographic equipment
13. Simplified diagram of radio equipment feed
14. Simplified diagram of crew's facilities equipment
15. Simplified diagram of the fuel system (fuel)
16. Simplified diagram of the fire fighting system (neutralization)
17. Simplified diagram for starting
18. Simplified diagram of the chassis.

Column 6, (G - wire indexes):
1. E; 2 - A; 3 - BA; 4 - FA; 5 - M; 6 - C; 7 - H; 8 - I; 9 - AP; 10 - L; 11 - S; 12 - Ph; 13 - R; 14 - CF; 15 - F; 16 - FF; 17 - St; 18 - Ch.

Remarks:

1. If any function in a given aircraft is absent, the numbers corresponding to it remain free.
2. The distribution of busbars are assigned letter indices A, B, and C, to the direct-current busbars; and D, E, F, to alternating current busbars.
3. For testing equipment the general order of numeration of systems, units, wires, and the distribution busbars, are retained with the addition of letter I, for example:

7200-1I is the simplified diagram of the d-c electric power system of the testing equipment.

801 I - is the instrument for the testing equipment, and so forth.

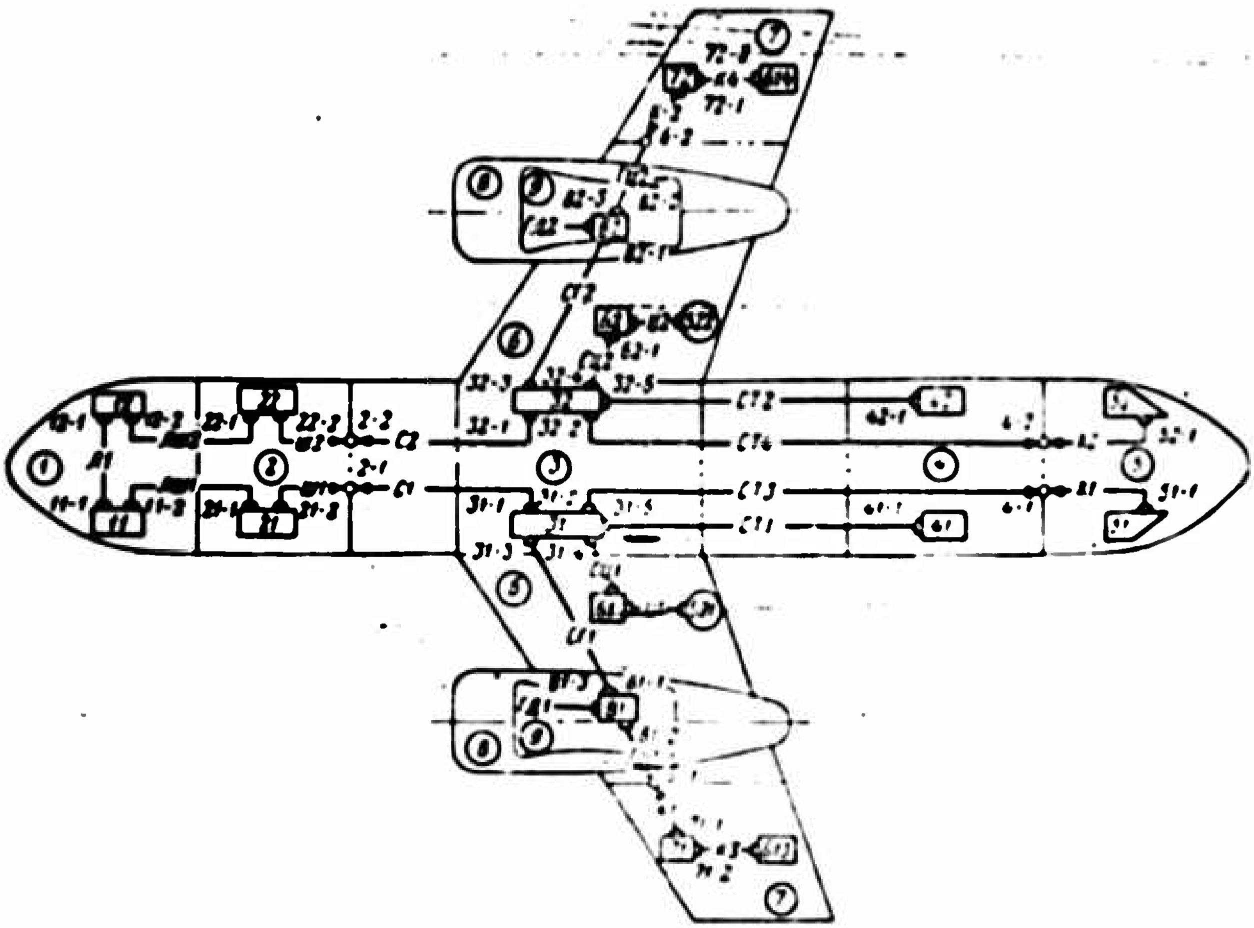


Fig. 2.4 - System of Numeration of Bunches of Conductors and Connecting Plugs.

In the conventional designations of the photographic wiring diagrams of the panels, the figures after the dash signify the numbers of the panels.

For example: 7210-0 - is the wiring diagram of electrical equipment of the pilot's cockpit; 7221-0 - is the designed blueprint of the left distribution installation of the navigator's cabin; 7210-11, 12 ... 19 - are the photographic wiring diagrams of 11, 12 ... 19, of the flyer's cockpit.

Table 2.3: Compartment Numeration System

C	D	E	F	G	H	1	2	J	K	L	M	N	O
		A Отсеки								B			
№	Наименование отсека	№ монтажной схемы	№ спецификации проводов	№ жгутов	№ разъемов			№ конструкции установок	№ панелей	№ блоков	№ разъемов	№ фидерных секций	№ структурных сетей
1	Кабина летчика	7200-110	7200-310	Л1, Л2 P1:P2	1-1,1-	2	7210.0	7210-100, 101, 102...	11 12 19	7200-111 7200-112 7200-119	11-1, 11-2 12-1, 12-2 19-1, 19-2	7210-11 7210-12 7210-19	7211-0 7212-0 7219-0
2	Кабина штурмана	7200-120	7200-320	Ш1, Ш2 N1:N2	2-1,2-	2	7220.0	7220-100, 101, 102...	21 22 29	7200-121 7200-122 7200-129	21-1, 21-2 22-1, 22-2 29-1, 29-2	7220-21 7220-22 7220-29	7221-0 7222-0 7229-0
3	Средний отсек	7200-130	7200-330	C1, C2 C	3-1,3-	2	7230.0	7230-100, 101, 102...	31 32 39	7200-131 7200-132 7200-139	31-1, 31-2 32-1, 32-2 39-1, 39-2	7230-31 7230-32 7230-39	7231-0 7232-0 7239-0
4	Технический отсек	7200-140	7200-340	T1, T2 T	4-1,4-	2	7240.0	7240-100, 101, 102...	41 42 49	7200-141 7200-142 7200-149	41-1, 41-2 42-1, 42-2 49-1, 49-2	7240-41 7240-42 7240-49	7241-0 7242-0 7249-0
5	Хвостовой отсек	7200-150	7200-350	X1, X2 TC	5-1,5-	2	7250.0	7250-100, 101, 102...	51 52 59	7200-151 7200-152 7200-159	51-1, 51-2 52-1, 52-2 59-1, 59-2	7250-51 7250-52 7250-59	7251-0 7252-0 7259-0
6	Центроплан	7200-160	7200-360	Ц1; Ц2 CP	6-1,6-	2	7260.0	7260-100, 101, 102...	61 62 69	7200-161 7200-162 7200-169	61-1, 61-2 62-1, 62-2 69-1, 69-2	7260-61 7260-62 7260-69	7261-0 7262-0 7269-0
7	Крыло	7200-170	7200-370	K1; K2 W	7-1,7-	2	7270.0	7270-100, 101, 102...	71 72 79	7200-171 7200-172 7200-179	71-1, 71-2 72-1, 72-2 79-1, 79-2	7270-71 7270-72 7270-79	7271-0 7272-0 7279-0
8	Гондола двигателя	7200-180	7200-380	Г1; Г2 EN	8-1,8-	2	7280.0	7280-100, 101, 102...	81 82 89	7200-181 7200-182 7200-189	81-1, 81-2 82-1, 82-2 89-1, 89-2	7280-81 7280-82 7280-89	7281-0 7282-0 7289-0
9	Двигатель	7200-190	7200-390	Д1; Д2 E	9-1,9-	2	7290.0	7290-100, 101, 102...	91 92	7200-191 7200-1.2	91-1, 91-2 99-1, 99-2	7290-91 7290-92	7291-0 7292-0

A - Compartments
B - Panels
C - Number of compartment
D - Name of compartment
E - Number of partial wiring diagram
F - Number of wire specification
G - Number of bunches of conductors
H - Number of connecting plugs
I - Number of wiring diagram
J - Number of structural installations
K - Number of panels
L - Number of photographic systems
M - Number of connecting plugs
N - Number of photographic wiring diagrams
O - Number of design blueprints.

1. Pilot's cockpit
2. Navigator's cabin
3. Middle compartment
4. Technical compartment
5. Tail compartment
6. Central plan
7. Wing
8. Engine nozzle
9. Engines.

Remarks:

1. If some compartments are absent in the particular aircraft, the numbers pertaining to it remain free.
2. If in some compartment the numbers there used, are insufficient, we introduce additional numbers with the zero index: 011, 012,...... accordingly the following numerations of the photographic diagram are produced: 7200-0111; 7200-0112; .... the auxiliary numbers should be assigned to splinter-boxes, small boards, and panels.
3. Only such panels should be separated into individual structural subgroups, which have an independent number and a considerable volume of structural blueprints. The minor structures of the splinter-boxes, small boards, and panels, etc., should be coded according to the subgroups of the corresponding compartments.
4. For wire bunches connecting two or more compartments, the letter index is given in accordance to the names of the compartments.
5. For testing equipment the general numeration order is retained for the blueprints, compartments, panels, connecting plugs, and their bunches, with the addition of letter I. For example: 7200-1101 is the partial wiring diagram of the testing equipment of the flyer's cockpit.; K121 is the bunch of conductors of the testing equipment of the right wing, etc.

General Purpose Structures - namely connection arose for feed at the airport, battery containers, sockets for the fuses, etc., may be transferred from one type of aircraft to another without changes. In that case only the places of their installations in various compartments change depending on the type and modification of the aircraft. Such a structure should be separated into special subgroups, not connected with a specific compartment.

A complex system of numeration of the blueprints with respect to the compartments is given in Table 2.3.

4. Direct Method of Construction of a Schematic Circuit Diagram.

Schematic circuit diagrams reflect the electrical relationships between the elements and disclose the principles of interaction between individual elements of electrical systems and the entire complex of electrical equipment.

Schematic diagrams are the principal working document in plotting, assembling, and operation of electrical equipment form the moment of origination of the draft to the termination of service of the aircraft, therefore, they should contain all the principal elements of the electric assemblies, switching equipment, and electrical system, with the images portrayed simply and clearly.

On the basis of the schematic diagrams the partial wiring diagrams, photographic and general wiring diagrams, and their structural installation blueprints are developed, their load circuits are plotted, and their required regulations are performed.

For certain types of aircraft, schematic circuit diagrams are used for 15 - 20 years. During this period, tens of thousands of people of various qualifications and levels of knowledge operated with them, beginning with the worker and ending with the highly qualified engineer.

Let us examine the possible ways of systematization in determining the schematic electric circuit diagrams.

The systemmatization is based on the principle of dividing electrical equipment according to functions. For each function, a separate schematic diagram is developed, which is assigned a specific number with the corresponding numeration of the units and wires.

On the schematic diagrams the electrical units and elements of the electric system are depicted conventionally, while the electrical connections between the them are shown with lines, which should have the most possible numbers of intersections and inflections. Power circuits are shown with wavy lines, electrical units with a conventional outline drawn with thin lines, inside of which the elements included in the assembly are shown. On the boundary of the outline the numbers of the terminals are marked (for units with several plugs, the number of these connection plugs are also marked), to which the external wires are connected.

It is sufficient to reveal the content of the internal elements for only one of the repeated assemblies of the same type, and for the other it is sufficient to mark only the exterior outline and number of terminals.

For electrical assemblies having a complex system, the picture of the internal elements should be given in a simplified way-band assuring the simplicity of understanding of electrical systems. In individual cases the interior elements should not be depicted, only the outline should be drawn with the terminal numeration and their brief subscripts indicating their purpose.

The conventional image of the protective device should be portrayed in accordance with its type. On the conventional outline, the rated current of the protective device is marked, and next to it the rated current of the consumer under long and short working regimes. The time of the brief working regime and the distance to the farthest point of the feeder.

This makes it possible to compile easily the load schedule, and select the power of the feed source, the type of protective equipment and to determine the cross-section of the wires.

If the protective device performs simultaneously the role of the switch, then one-half of its conventional symbol is sheeted or is shown in the disconnected position.

On the diagrams near the conventional images of the circuits, the cross-section of the wires corresponding to them are marked. If the wire cross-section is constant for all the sectors of the feeder line, it is marked at the section closest to the protective device.

If the wire cross-sections vary in the different sections of the system, it is marked at all the sections of the system.

Shielded wires are marked with crosses.

Near the conventional protection symbol the name of the feeder should be marked. For example: "Eleron trimmer".

In cases where the work of the system depends on its initial position, near terminal switches, relays, electrical units, etc., it is necessary to make the appropriate explanations in the diagrams. The absence of such explanations (subscripts) renders difficult reading of the diagram and results in their incorrect comprehension and operation.

It is desirable to place the description under the corresponding feeder line in the diagram.

In the specifications the units are enumerated according to increasing numbers, as it is indicated in Table 2.4.

This form of specification makes it possible to determine easily the functions, the type of the unit, the number of the compartment, of the panel and the installation blueprint.

The three numbers are also entered into the table and used in installing additional units.

The name of the units should be brief, precise, and correspond to the standard designations on the parts and sections.

Table 2.4

1	2	3	4	5	6
		[illegible] агрегата	Тип	№ установочного чертежа	Примечание
		7 [illegible]	13 [illegible]	7290-20	
		8 [illegible]	14 [illegible]	7290-20	
[illegible]		9 [illegible]	15 [illegible]	7281-0	$I_{ном}$ 100 а 17
[illegible]	[illegible]	10 [illegible]	16 [illegible]	7282-0	$I_{ном}$ [illegible] а 18
[illegible]	105	11 [illegible]	2В-15	7222-0	
[illegible]	106	12 [illegible]	2В-15	7222-0	

1. Number of compartment of panel
2. Number of unit
3. Name of unit
4. Type
5. Number of installation blueprint
6. Remark
7. Left generator
8. Right generator
9. Inverse current relay of the left generator
10. Inverse current relay of the right generator
11. Left generator switch
12. Right generator switch
13. GSR-9000
14. GSR-9000
15. DMR-400 A
16. DMR-400 A
17. I_{NOM}
18. I_{NOM}

For example: the "light" of left landing light switch. The schematic diagram gives additional specifications of the manufactured articles, which have a great importance in the solution of a number of problems in planning and operation of electrical equipment. The specification form is given in Table 2.5.

Table 2.5

1 № п/п	2 Наименование агрегата	3 Тип	4 Количество	5 Вес 1 шт. кг	6 P вт	7 U в	8 I а	9 Примечание	
1	10 Генератор	ГСР-9000 15	2	21	9000	28,5	300	100 а 1 мин 600 а 10 сек	13
2	11 Реле обратного тока	ДМР-400 16	2	1,85		28,5	100	Разрывная способность 3000 а	14
3	12 Регулятор напряжения	Р-25АМ 17	2	1,75		28,5	1,5		

1. Cardinal number
2. Name of unit
3. Type
4. Quantity
5. Weight of 1 item kg
6. P Watts
7. U Volts
8. I - Amperes
9. Remark
10. Generator
11. Inverse current relay
12. Voltage regulator
13. 400 a - 1 min; 600 a - 10 sec
14. Breaking capacity 2000 a
15. GSR - 9000
16. GMR - 400 A
17. R - 25 AM

Compilation of the specifications does not require additional time expenditures since in the development of schematic diagrams a considerable time is devoted to familiarization with the principles of action and the principal parameters of the manufactured articles.

On the schematic diagram of an electric power system the distributing bus-bars with the protection devices and the names of the feeder lines of the consumers according to the functions are portrayed. This makes it possible to visualize clearly and distinctly the electric power system of an aircraft with all the distributing devices and the location of the consumers (see figure 1 of the appendix).

In finishing these schematic diagrams for series produced aircraft in excess of connecting plugs and their number of terminals to which the wires are attached a path should be introduced, as it is shown in fig. 2.5.

When the connecting plug indices are available with indication of the number of terminals, the control of electrical systems for an aircraft is greatly simplified, the time for the control is reduced, and during operation it is no longer necessary to have partial wiring diagrams, with which it is much more diffuclt to perform control than with the above mentioned simplified circuit diagrams.

Compilation of schematic diagrams according to functions has the following advantages:

1. It simplifies planning, installation, and operation of the systems. It is possible, without additional time-loss, to use them for drafts and blueprints and for all manner of coordination in the process of planning and finishing the details of electrical equipment of an aircraft.

2. The project work-front is expanded.

3. The planning time is reduced.

4. A more profound working-out of the system is provided.

5. It becomes possible to use less skilled designers without damage to the design quality.

6. It becomes possible to modify substantially the electrical equipment of the aircraft in exceptionally brief periods of time

7. The time for studying the systems in assembly and operational aircraft is reduced substantially.

8. The replacement of worn-out tracing papers is simplified.

9. The probability of basic and former errors in electrical systems is decreased.

10. The preparation is simplified and the time for making out documents for ordering the finished articles is reduced.

11. It becomes possible to determine easily the weight of the finished articles according to their functions, the power consumed, and other parameters.

5. Method of Plotting Partial Wiring Diagrams.

The partial wiring diagrams reflect the actual position of electrical units on an aircraft and their external electrical connections.

The partial electrical wiring diagrams are developed on the basis of simplified systems and made for every compartment, in accordance with which they are assigned a number.

On the partial wiring diagram the conventional circuit of the aircraft compartment is given in which the units, panels, and the connecting plugs are indicated. Their location in the system should approach the actual location of their installation in the aircraft.

On the connection pictures the numbers of the terminals are marked and the male and the female plugs are also marked. The female plugs should be located on the side of the current carrying part.

Wires connecting individual elements of electrical equipment with one another, are connected in bunches, in this way providing the most

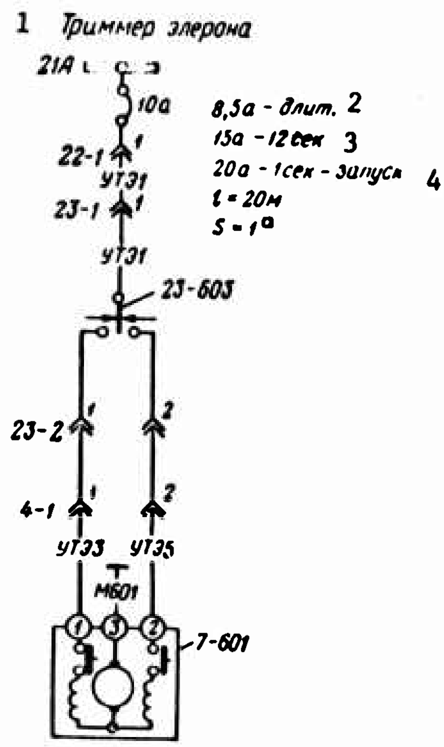


Fig. 2.5. Schematic diagram with indication of the path of the wires.
Key: 1. Eleron trimmer; 2. 8.5 a - long; 3. 15 a - 12 sec; 4. 20 a - 1 sec - start.

rational communications possible.

Depending on the character of assembly (open, in a shield, in a pipe) the bunches have their specific symbols.

The schematic location of the bunches should be brought close to the actual assembly conditions. Avoiding excessive intersections, which simplifies considerably a reading of the diagrams and a carrying out of the subsequent operations.

In developing partial wiring diagrams, the following design, technological, and operational requirements should be fulfilled: 1. Rational grouping of units, assuring the minimum weight, the maximum reliability and convenience of operation. 2. Technological efficiency of manufacture of the units, wire bundles and their assembly on the aircraft. 3. The minimum quantity of plug connections. 4. Minimum length of wire communications. 5. Minimum number of branches in the bundles. 6. Simplicity of removal of bundles, panels and units. 7. Provision for operational accessibility for examination of the equipment. 8. Limited use of the splinter-boxes, serving for technological distribution. 9. Simplicity in depiction of the diagrams.

The specification for the units for the partial wiring in a diagram is made in the form of simplified diagrams. At the beginning of the specifications in the order of increasing numbers the panels of the given compartment are indicated. Further, in increasing numbers with adherence to the order of the functions the specifications of the units are given. At the end of the specifications also in the order of increasing numbers the connecting plugs installed in the given compartments are enumerated. This form of specification simplifies the reading of the partial wiring diagram and its coordination with the simplified diagrams and design blueprints.

For the partial wiring diagram for each compartment a specification is made for the wires with indication of the number of the units, panels, plug-connections, length, types, and cross-sections of the wires.

To decrease the weight of the wires the units should be fed from the servicing devices, located in the immediate proximity from them.

Units installed in the crew's cabins and the unit control circuits located in other compartments should be supplied with power from the crew's cabins.

In the process of development of partial wiring diagrams it is necessary to strive for a rational grouping of electrical equipment elements in the compartments and the panels from the point of view of the minimum weight, simplicity of design, technological effectiveness, reliability, and simplicity of operation in the electrical equipment of the aircraft.

Photographic Diagrams are developed for the distributing devices, instrument boards, panels, shields, switching boxes, and other aircraft units, and are used in the process of operation and electrical installation.

In the first case the photographic diagrams are printed on photosensitive paper or metal and installed in the corresponding units of the aircraft. The photographic diagrams should have a black background and white image. The dimensions of the photographic diagrams are selected in accordance with the place of their installation, but in such a way as to provide for clarity of the image and reading convenience. The arrangement of the units on the photographic diagram should correspond to their actual position on the panels, which simplifies considerably the operation of the electrical equipment.

In the second case the photographic systems are used in carrying out electrical assembly operations on ducts, for which purpose they give the specification of the wires with indications of the type, length, and cross-sections.

The cross-sections of the wires inside the panels should correspond to the cross-sections of the suitable wires. However, in order to decrease the weight and for the sake of compactness of electrical assembly within the panels it is advisable to use wires without chlorovinyl braiding and with smaller cross-sections, in comparison with the suitable wires, without disruption in doing this, the permissible values of the current load. This pertains primarily to wires, the cross-sections of which are selected according to the voltage drop or from considerations of mechanical strength.

If a large number of the wires of the same type and cross-section, then, for the experimental aircraft it is sufficient to mention this in the remarks.

6. Methods of Plotting the Wiring Diagrams.

Wiring diagrams are the principal technical documents in the assembly of the electrical system of an aircraft and at the same time are the systems of communications of the wires and the arrangement of the equipment, the list of the installation blueprints, the weight summary, and finally, the grouping of the electrical equipment for the given compartment.

In order to reduce the assembly time, decrease possible errors, raise the quality of the assembly and reduce the weight, the wiring diagram should be developed in the process of experimental planning and refined in the final adjustments of the experimental model.

Let us examine the most rational system of formation of wiring diagrams.

Wiring diagrams are usually made for individual compartments, that is, they are portrait within the outline of the framework of the corresponding compartment of an aircraft on a scale, of 1:5 or 1:10 as a rule.

The structural details of boxes, panels, arms, and other elements, required for assembly, are marked on the diagram on the same scale, as well as all the electrical units, panels, shields, and the plug connections of the given compartment with indication of the number of installation in the blueprints and the corresponding numbers of the units and plug connections according to the partial wiring diagram. If the units are installed on the panel, then only the number of the panel is given.

Then all the bunched conductors are marked in accordance with their actual position in the aircraft and with indication of their numbers. The details and norms for fastening the bunches are indicated.

In order to simplify the installation of the bunches of the fuselage compartments and nozzles the wiring diagrams should give the principal plan projection and views of the right and left side from the inside. In places where the bunches of conductors pass from side to side, in order to clarify the specific units for fastening and laying the bunches, the general blueprint should give the types and units of the corresponding places.

On the wiring diagrams made for experimental airplanes, the passages and fastenings of the wire-bunches on the main routes are worked out in details.

The routes of the minor bunches of conductors and their single wires are marked down tentatively and rendered more precise when the installations are more refined on the experimental aircraft.

In refining the routes and fastening details for the bunches of conductors it is necessary to use photography extensively and to compose photographic albums in the form of diagrams.

Photographic albums are given to the series producing plants where the item is to be produced in series.

The internal assemblies of the panels and boards are not indicated, and only the numbers of the installation blueprints and numbers of photographic diagrams are given.

Publication of photographic albums (blueprints) gives a good concept on the details of wiring without loss of the designer's time. This method of showing the wiring details should be called the most maneuverable and economical.

The specifications for the wiring diagrams are composed according to the form indicated in Table 2.6. The specification includes all the electrical units installed in groups 72 and other groups, and also the bunches and fastening norms. The specification makes it possible to determine easily the numbers of the electrical units, the bunches and installation blueprints, the location of the unit on the aircraft, the weight of individual installations and the weight of the electrical equipment of the given compartment.

Table 2.6.

1 № агрегатов, пультов разъемов, жгутов	2 № чертежа	3 Наименование установки	4 Количество	5 Материал	6 Вес кг	7 Примечание
111	—	Жгут 8	1	Сборочный 11	1,6	14 В экране
11	7211-0	Левое РУ пилота 9	1	Установочный 12	25,3	
105	7210-100	Регулятор напряжения 10	1	То же 13	2,1	

Key: 1. Number of the aggregates, [illegible]els, plug-connections, bunched conductors; 2. Number of the blueprints; 3. Name of the installation; 4. Quantity; 5. Material; 6. Weight kg; 7. Remarks; 8. Bunch; 9. Pilot's left distribution system; 10. Voltage regulator; 11. Assembling; 12. Installation; 13. Dc; 14. Shielded.

Their specification is arranged in the order of the increasing numbers.

The recent practice of placing the typical building-in of the wires, connections, bunches, and other typical assembly elements on wiring diagrams causes the repetition of single type units, additional errors, and substantial time-losses, therefore, in developing the wiring diagrams we should use widely the norms of the standard wiring elements and units, used for various types of aircraft. The norms should be supplemented systematically upon the appearance of new building-in methods.

Drawing of wiring diagrams in the process of planning and their refining during assembly of experimental models by photography reduces the total time-loss for planning and assembly, reduces the weight and increases the reliability of electrical systems.

Photographic Wiring Diagrams. The practice of developing and publishing wiring diagrams for panels, shields, and instrument boards, distribution systems, and other electrical units, is connected with great difficulties and considerable time-loss. Given in the series' production plants the finishing of blueprints lacks behind the actual changes in wiring diagrams. For experimental models it is practically impossible to develop such blueprints. Therefore, it is quite rational to use photographic wiring diagrams, which show high quality of the diagrams with a minimum time expended for designing.

The panels, boards, and other electrical units under the experimental plans are usually assembled by highly qualified electricians. This assembly is thoroughly refined with the participation of the designer, and photographed with provision of good visibility of all the details. The photographs are assigned the blueprint number. The necessary details and fastening norms are included into the specifications.

The blueprint of the photographic wiring diagram is the principal technical document in the assembly of experimental and series' produced aircraft. The photographs are reviewed when the design is rendered more precise.

For connecting wires in carrying out the assembling work the corresponding photographic wiring diagram is used.

7. Procedure for Plotting the Feeder Circuit Diagrams.

The saturation of modern aircraft with electrical-equipment units makes it necessary to create feeder diagrams which simplify the orientation in the electrical systems during operation (checking, repairs, elimination of defects), analysis of reliability, and determination of the weight of the feeder elements.

The feeder diagrams are formed for individual consumers, or a group of consumers, which have a common purpose, a single common protection apparatus, or several protection apparati, serving a group.

The feeder systems are the supplementary sub-division of the simplified diagrams of each function with the addition of a partial and a complete wiring diagram part. Some schematic diagrams, drawn according to the functions, pass over completely into the feeder diagrams without any additional splitting. The typical diagram is given in fig. 2.6.

The development of either diagram is based on the schematic, partial, and complete wiring diagrams, the structural principles of which extend completely onto the feeder diagrams.

For the greatest obviousness and simplicity in employment, the feeder diagram should include six basic elements:

1. Simplified diagram of a feeder with indication of the path of the wires (numbers of connections and terminals).
2. Partial feeder diagram for the entire circuit of the aircraft.
3. Wiring diagram of the feeder, portrait in isolectric or plant projections for the entire circuit, with marking of the true position of the units, panels, and the wire bunches.
4. Specification of the feeder wires with indication of their type, cross-section, length, and weight.
5. Specification of the units of the given feeder.
6. Brief indications of the possibilities of the work of the system's elements. The feeder systems should be worked in preparation of the description of the experimental aircraft and used later for all types of technical information on electrical equipment.

Chapter 3. Stages in Planning the Electrical Systems of Aircraft.

1. Planning Stages.

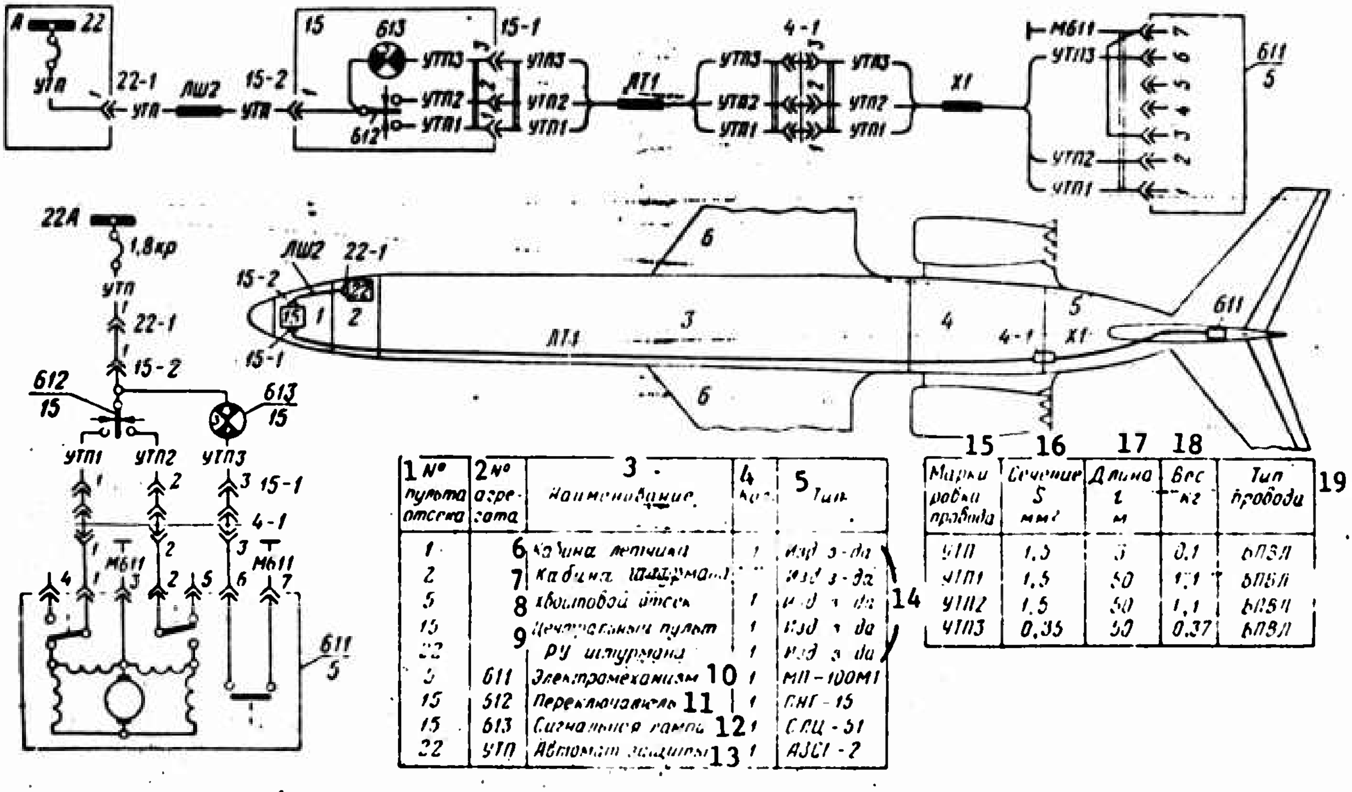
The process of planning of the electrical systems of aircraft passes through the following stages:

1. Draft planning.
2. Modeling.
3. Work planning.
4. Assembly of the experimental model.
5. Industrial testing of the experimental model.
6. Stage testing of the experimental model.
7. Beginning of series production.

At all the planning stages theoretical and experimental investigations of various variations of electrical systems are performed continuously, as a result of which at the moment of starting of series production of the aircraft the optimum variation with the refined prospective equipment is determined.

The successful planning of electrical systems for the experimental aircraft depends to a great extent on the depth and volume of the theoretical and experimental investigations of the models, experimental-series types of equipment and of the systems as a whole.

For this purpose orders for prospective equipment should be placed before the beginning of planning of the experimental aircraft in order



1 № пульта отсека	2 № агрегата	3 Наименование	4 Кол.	5 Тип
1		6 Кабина летчика	1	Изд з-да
2		7 Кабина штурмана		Изд з-да
5		8 Хвостовой отсек	1	Изд з-да
15		9 Центральный пульт	1	Изд з-да
22		РУ штурмана	1	Изд з-да
5	611	Электромеханизм 10	1	МП-100М1
15	612	Переключатель 11	1	ПНГ-15
15	613	Сигнальная лампа 12	1	СЛЦ-51
22	УТП	Автомат защиты 13	1	АЗСГ-2

14

15 Маркировки провода	16 Сечение S мм²	17 Длина l м	18 Вес кг	19 Тип провода
УТП	1.5	5	0.1	БПВЛ
УТП1	1.5	50	1.1	БПВЛ
УТП2	1.5	50	1.1	БПВЛ
УТП3	0.35	50	0.37	БПВЛ

Fig. 2.6. Feeder Diagram. Key: 1. Number of the compartment panel; 2. Number of the unit; 3. Name; 4. Quantity; 5. Type; 6. Pilot's cockpit; 7. Navigator's cabin; 8. Tail compartment; 9. Navigator's central distribution system panel; 10. Electrical mechanism; 11. Switch; 12. Signal lamp; 13. Automatic protection device; 14. Plant publication; 15. Wire markings; 16. Cross-section; 17. Length; 18. Weight kg; 19. Types of wires.

to accelerate its production and be able to select the optimum equipment at the beginning of planning, which would provide a maximum reliability, minimum weight, and simplicity in operation.

2. The Draft.

The draft in the initial and determining stage in the development of electrical systems of the experimental aircraft. During this period the basic theoretical and practical problems are solved and the basic technical documents on electrical equipment is developed.

Technical documents should have a general group character, but with a theoretical substantiation of the basic problems of principle, should also be illustrative, precise, clear, and convenient for solution and coordination of the principal problems with adjacent organizations, in order to carry out experimental works, modeling, and work planning. This detailization should be carried out at the work planning stage.

The combination at the beginning of planning of electrical systems with the moment of inception of the draft of the aircraft has a positive effect on the entire course of the process of planning and construction of the aircraft.

At the draft stage, a comprehensive examination and detection of the principal possibilities of the consumers, the character and the specific features of their operation are performed. The required capacities for flight stages are determined. The principal type of the current is selected. A comparative analysis of the reliability and weight of different variations of electrical equipment is carried out. Simplified diagrams of power systems and their principal consumers are worked out.

On the basis of these works the manufactured articles are ordered, experimental work is performed for determining the optimum variation, the electrical equipment is arranged in groups, the aircraft model is built with the equipment arranged in it, and the working planning is performed. This makes it possible, by the beginning of the work planning, to have specific solutions of all the principal problems on the electrical equipment of the aircraft.

At this stage of the draft planning the following problems should have a substantiated solution:

1. Development of simplified electrical systems.
2. Selection of electrical equipment.
3. Selection of type of current in the primary power system.
4. Selection of the voltage, number of phases, and frequency.

5. Selection of the type and number of sources of electrical energy.
6. Calculations of electrical parameters.
7. Development of systems of functional relationships between the systems.
8. Development of simplified partial assembly of electrical systems.
9. Arrangement of the distribution devices in groups.
10. Grouping of the electrical equipment.
11. Grouping of the electrical conductor bunches according to the principal lines.
12. Compilation of the technical requirements for the first electrical equipment.

Let us examine in brief the content of the above mentioned problems.

Development of Simplified Electrical Systems. The draft should be necessarily accompanied by a sufficiently detailed devlopment of the simplified electrical systems simultaneously in several variations with subsequent selection of the most rational one of them.

The content and appearance should approach the work planning electrical systems. This simplifies the process of grouping of the equipment on an aircraft, makes it possible to determine the possibilities of the optimum solutions of equations of principle, to determine the necessity for developing new equipment, carrying out the most rationally design, model, and their work planning.

Special attention should be devoted to the development of the simplified electric power system, since it determines the rationality, character, and grouping of the rest of the electrical equipment.

The basic electrical systems should be made with a high degree of precision, since the errors permitted in them are repeated many times in all the blueprints derived from them.

In order to signify the grouping of electrical equipment and tie in the operations with the adjacent organizations, it is advisable to draw simplified, partial wiring diagrams on the plug diagram blueprints with indication of the quantity and cross-section of the wires.

Selection of Electrical Equipment. In accordance with the simplified electrical diagrams a detailed list of electrical equipment according to the functional features is made. In this case the type, capacity, working time and special operating conditions are indicated. The list of electrical equipments serves as the initial material for grouping, load-schedule compilation, and slection of capacities and types of energy sources.

In the process of planning the characteristic operation features are determined as well as the principal technical parameters of the electrical units, the optimum set of equipment is established, the possibilities of the use of a series' produced manufactured articles and the necessity of development of new ones taking into account the latest achievements are also determined.

It is necessary, to use as much as possible the series' produced electric units or experimental units, which have passed the state test. This reduces substantially the time required for planning and construction of aircraft. However, in order to improve continuously the technical and operational qualities of the aircraft, the latest prospective electric equipment should also be developed. The process of creation of this equipment should be far ahead of the dates of planning of the aircraft, and as a rule, should be carried out with the intention of using it in various types of prospective aircraft. It is advisable to examine simultaneously several variations of electrical systems and types of principal consumers. Special attention should be devoted to main consumers, since they exercise the main influence on the selection of the type of current, voltage, number of phases, frequency, power, and type of source.

Selection of the Type of Current. In aircraft both direct and alternating current are used simultaneously, and depending upon the proportion of capacity one of them is the principal (primary), and the second is the auxiliary (secondary).

Direct Current with a voltage of 27 v has passed along operational testing. It is reliable and safe. It has perfected voltage regulation equipment and equipment for parallel work of the energy sources. Direct current is used most reliably for the work of electromagnetic devices (relays, conducts, etc.), and incandescent lamp produce a better illumination effect. However, the d-c system a considerable weight and low efficiency in the transformation of energy. At high altitude there is a problem of switching, brush-contact, and cooling.

Alternating Current with a voltage of 200/115 v is beginning to attain primary importance. It is easily transformed with respect to voltage and frequency, and makes it possible to raise the ceiling of the equipment, reduce the weight and simplify the machine's design. In several types of aircraft the use of a-c motors with short circuit rotor is a sufficient reason in favor of the alternating current.

However, up to the present there are no simple and reliable methods for assuring the stability of the frequency and parallel work of the energy sources, which results in a complication of the electric power system and a relative reduction of reliability.

In order to select the type of current for the primary power system the consumers are divided into three groups and their total capacity is determined taking into account the coefficient of simultaneous searching on:

1. Consumers, requiring feed with only d-c (electro-magnetic trains, control circuits, synchronization, and instruments).
2. Consumers requiring supply of only a-c (certain types of radio communication, radar, navigation, automatic, and manually operated equipment).
3. Consumers for which the type of current is unimportant (heaters, lighting devices, electric motors for the pumps, and certain types of radio equipment).

Taking into account the general requirement for electric power, its separation into groups, and also the principal requirements for feed of individual consumers, the principal type of current selected for the primary power-system of the aircraft.

For the principal type of current the initial energy sources are installed, the rationality of installation of the primary sources of energy for the auxiliary type of current is determined by the value of the power required. Sometimes it is reasonable to produce auxiliary type of current by transforming it from the principal type of current. This source is being used most extensively for small capacities.

It is necessary to exclude completely the widely accepted practice of using consumers and energy sources of various types of current, voltage, phase number, and frequency, since it decreases considerably the reliability and increases the weight of the electrical equipment.

Sub-Subreading, Selection of Voltage, Number of Phases and Frequency.

Voltage. The selection of the rated voltage depends on the purpose and dimensions of the aircraft, the amount and power of the consumers. The optimum voltage is determined by the calculation method and should be standard.

For direct current (proceeding from the condition of service safety) the 27 v voltage is the most rational. The use of higher voltages is sensible only for heavy aircraft, however it has not become widely used.

For alternating current (proceeding from the condition of the minimum weight) the most reliable voltage is 200/115 v with a grounded neutral powerline).

Number of Phases. With respect to weight, the most rational is a three-phase operating current, but a more complicated protection and switching is required for it.

For small power consumers it is more rational to use a single-phase alternating current, using the neutral powerline with a strict regularity of distribution of the loads according to phases.

Frequency. The optimum frequency for the entire complex of aircraft equipment should be considered the 400 cps frequency also for individual consumer the 800, 1000, 1200 and 2000 cps frequencies are better.

Selection of Type and Number of Sources of Electrical Energy. The selected type of current, voltage, number of phases, frequency and capacity of the consumers determine the type and power of the energy sources, while their minimum quantity is determined by the number of aircraft engines.

In the process of planning an aircraft, the quantity and power of consumers as a rule increase before the value of the capacity should be increased up to 50% in comparison with the capacity determined in the initial stage of planning.

In the selection of the generators, a power-reserve equal to 50-100% over the medium load should be assured, depending on the type and purpose of the aircraft.

Calculations of Electrical Parameters. According to the simplified diagrams and working conditions of the electrical units, the required powers are calculated with respect to functions, the load schedules for the energy sources are plotted under various flight conditions, and calculations are performed for the cross-sections of the wires and weights of the electrical systems.

In this case it is reasonable to perform comparative calculations of various variations of the diagram for the same system, which makes it possible to determine the optimum variation of the diagram. In this case the generalized materials on the systems are planned earlier and render substantial aid.

Development of Functional Connection Diagrams between the Systems. Modern aircraft are equipped with complex electrical, electronic, radio-communication, and radar systems.

The work of the systems, as a rule, is automatic and interrelated with various signals, commands, and their performance, and in order to coordinate the entire work of the equipment it is necessary to work out diagrams of functional communication between systems.

A diagram should include all the principal units and their relationship, directions of the movement of signals, commands, and their fulfillment, parameters of the signals, and commands, their quantity in cross-sectional wires in the communication and the principal requirements to the individual units and systems.

Development of Partial Wiring Diagrams. Simplified partial wiring diagrams should be developed for individual compartments on the basis of simplified diagrams.

As has been noted earlier at the stage of the draft-planning the development of simplified partial wiring diagrams is permitted, which should be portrait on the blueprints of the simplified circuit diagrams. This makes it possible to solve the afore mentioned problems with a minimum time-loss in planning.

Grouping of the Distributing Devices. Rational Grouping of distributing devices should be provided for in the development of the simplified diagram of the power system. The central distributing systems (CDS) as a rule should be placed near the generators and principal power consumers. From the CDS, power is supplied to the power consumers and secondary distributing systems (DS) located mainly in the crew's cabins. The latter provide power to minor consumers and the electric system regulation circuits.

In the CDS and DS protection is grouped according to functions, and within the functions according to the purpose of the consumers.

Between the distributing busses, the energy should be transmitted accorded to the circuit, which provides a higher reliability of viability. In arranging the positions of the distributing devices, it should be borne in mind, that the systems of transmission and distribution of electrical energy according to the collection bus-system without protection of the feed lines are unreliable and present a fire hazard. The collecting bars have a great length and consequently a high short-circuit probability and therefore can cause serious damage and fires on the aircraft.

Layout of the Electrical Equipment. The layout of electrical equipment should take into account the influence of acceleration, vibrations, moisture, and temperature, should provide for the technological effectiveness of installation, convenience and reliability in exportation .

The electrical equipment units and cables should be installed in such a way that they could be examined and replaced with a minimum time loss.

In arranging the lay-out, the specific feature of operation of the electrical equipment should be taken into account. Thus, for example, to assure the reliable work of the current voltage regulator, its axis should be located perpendicularly to the longitudinal axis of the aircraft, and so forth.

Arrangement of the Bunches of Electrical Conductors along the Main Lines. The bunches of wires and their cables should be laid over the shortest distances and removed as far as possible from the hydraulic system, fuel system and moving parts. The bunches and their plug-connections should assure satisfactory air-circulation. The electric lines in conduits should be avoided as much as possible, and when necessary drainage and natural ventilation should be provided.

Compilation of the Technical Tasks for the New Electrical Equipment. During rough draft-planning in the development of simplified circuit diagrams it becomes necessary to use new electrical units.

The depth of the analyses and the thoroughness of working out of the simplified circuit diagrams take into account the emergency working conditions of the systems, make it possible to determine the most rational types of new electrical equipment. In accordance with the simplified circuit diagrams the technical tasks are prescribed and orders are made for development of new electrical equipment.

The rough draft is examined by the customer. The substantial remarks and the requests of the customer are included into the blueprints.

The rough draft is the basis for the further stages of planning.

3. Modeling.

In accordance with the draft a natural sized mock-up of the aircraft is built, in which the models of the electrical units, boards, panels, distributing systems, boxes, and other types of equipment are installed.

The rationality of the arrangement, design, technical effectiveness and convenience of operation of electrical equipment is checked on the model.

The model should approach in its details to the actual aircraft. The well-adjusted mock-up increases the quality and reduces the time for the working planning and construction of the experimental aircraft.

The mock-up is accepted by the model commission, and determines and eliminates the short-comings of the arrangements, taking into account the requests of the customer. The required finishing adjustments of the model are performed and the corresponding changes in the draft blueprints are made.

Parallel with the arrangement of the electrical units on the aircraft mock-up in the laboratories of the design bureau and the corresponding institutes the working models of the electrical systems with the natural equipment should be installed and investigated in accordance with the planned simplified electrical diagrams.

If the capacities of the electrical system are great, the testing is to be performed by physical simulation.

The operating models of the electrical system should be tested under normal and emergency working conditions.

Several variations of the electrical systems should be developed and examined simultaneously. According to the results of the tests the most reliable and light electrical systems are selected.

The complex test and final adjustments of the electrical system should be performed at all the aircraft planning stages.

Simultaneously, the adjacent design bureau should make models of and investigate the newly planned electrical equipment.

4. Work Planning.

In accordance with the rough draft, the model, and the results of laboratory investigations, the work blueprints are developed for the simplified, partial wiring diagrams, and wiring diagrams of electrical systems and structural installations. Final calculations are made for the powers used, energy power source schedules are plotted, calculations of wire cross-sections and electrical portection lines are performed. Short-circuit currents under emergency regimes are calculated, finished articles are refined, and the technical documents for the newly ordered equipment is given final adjustments.

The ideas behind the simplified circuit diagrams of the rough draft, should be practically transferred without changes to the blueprints. Changes in principle, may be introduced only as a result of detection of short-comings during a joint investigation of the electrical system by the manufacturer of the equipment, the laboratories and the design division, planning the aircraft.

The systems and the designs provided for by the blueprints should be simple, technological effective, convenient, and reliable in operation.

The technical recommendation should be presented according to the recommendations described in chapter 2.

5. Assembly of the Experimental Model.

Boards, panels, distributing systems, boxes, and other structural assemblies of electrical equipment are manufactured and installed according to the blueprints.

The internal assemblies of the units, should be carried out outside of the aircraft on work-tables, which reduces considerably the labor consumption and improves the quality of the assemblies.

In the process of assembly the basic and foremost errors permitted in the blueprints are detected and eliminated. During testing of the electrical systems under a current the defects and errors committed in the basic and partial wiring diagrams are detected and eliminated.

The blueprints should be refined only with technical remarks. In order to simplify work with blueprints the technical remarks should be formulated with a single number for the entire set of circuit diagrams connected with these changes. A large number of technical remarks makes it difficult to read the blueprints and especially the blueprints of electrical systems, therefore remarks should be entered into the blueprints periodically. At this stage it is necessary to refine thoroughly the assemblies, photographic, and production of photographic wiring diagrams.

6. Testing of the Experimental Model at the Plant.

During the test at plant the individual electric systems and the entire complex of electrical equipment are checked on the ground and under different flight conditions, the design, basic, and operational defects are discovered and eliminated.

Individual electrical systems owing to insufficient studies and tests at the preceding planning stages may be subjected to substantial changes, which halts back the completion dates and increases the cost of the experimental aircraft. Correct planning methods eliminate such phenomena.

The required changes are introduced into the blueprints.

7. State Testing of the Experimental Model.

During the state testing of the experimental model on the ground and in flight the electrical systems are checked in accordance with the technical purpose of the aircraft. The working capacity of the aircraft's electrical equipment is determined under normal and emergency flight conditions.

The artificial creation and the checking of individual emergency conditions of the electrical systems on a real aircraft may be connected with grievous consequences. In this case operating mock-ups should be manufactured and the investigation should be performed under laboratory conditions. As an example we may mention the laboratory investigations of the viability of power systems during short-circuits.

Operating mock-ups provide for a more profound and comprehensive investigation of the processes occurring under emergency conditions. Mock-ups with real equipment and power lines should be delivered for state testing when the aircraft is still in the stage of rough draft planning.

During the flight tests the basic, design, operational shortcomings in the electrical equipment of the aircraft are detected and ways to eliminate them are outlined. Insignificant defects are also eliminated in the process of testing.

According to the results of the tests a document is drawn up with indications of the defects and recommendations for adjustments. After the document has been studied the required changes are introduced into the blueprints and the adjustments of the experimental model are made. If the adjustments were of a basic character, the experimental model is delivered for repeated tests.

Individual measures for improvement of the systems' work may be introduced directly when the aircraft is put into series production.

8. Series Production.

Before putting the aircraft into series production adjustments, connected with elimination of defects determined during the modeling process, experimental production, plant and state tests are introduced into the blueprints as well as the changes caused by the technological features of series production.

The process of adjustment of the blueprints for series production usually proves very labor consuming and is connected with the production of a large quantity of additional technical documents. However, when the above examined system of rational planning is used, the process of reparation is simplified, the quality is improved, and the time for the output of technical documents for series production is reduced.

Section II. Weight and Reliability Criteria of Electrical Equipment of Aircraft.

Chapter 1. Weight Criterion of Electrical Equipment.

1. Flight Weight of Electrical Equipment.

The determination of the weight of electrical equipment of an aircraft begins with the analysis of the weights of the units installed, grouped according to functions (purpose) according to the basic circuit diagrams.

The weight characteristics of the electrical equipment are determined systematically, beginning with the elementary weight and ending with the flight weight of the entire electrical equipment of an aircraft.

The principal weight characteristics are as follows:

Elementary Weight of the Electrical Unit. This is the weight of its components. For the same capacity of an electrical assembly the elementary weights may vary depending on the structure of the electrical assembly, type of current, voltage, frequency, and installation conditions.

We give the symbols of the elementary weights of an electrical unit:

g_{1A} - is the weight of the electrical part of the electrical assembly (electric motors, relay, terminal switches, etc);

g_{2A} - is the weight of the mechanical part of the electrical assembly (drive, reducing gear, pump, etc.);

g_{3A} - is the weight of the external equipment, serving the electrical assembly (switches, relays, terminal switches, plug connections, etc.);

g_{4A} - is the weight of the powerline wires, installed in the aircraft for feeding the electrical assembly;

g_{5A} - is the weight of the installation structures for the electrical assembly (arms, stands, etc.);

g_{6A} - is the weight of the installation parts of the electrical assembly (boxes, pipes, hoses, colors, etc.);

g_{7A} - is the weight of the d-c power system used for feeding the electrical units;

g_{8A} - is the weight of the a-c power system used for feeding the electrical units;

g_{9A} - is the auxiliary weight of the aircraft caused by the installation of this unit (increase in weight of the aircraft engines, cooling systems, fuel, and so forth).

Let us give certain explanations on the determination of the elementary weights of the electrical assemblies.

The weights of the finished articles, the units and the switching equipment (g_{1A}; g_{2A}; g_{3A}), are determined according to the data of the technical description or by weighing.

The weight of the powerline wires (g_{4A}) is determined in accordance with their cross-sections and length specifically for the given type of aircraft. The weight of one running meter of the wire is determined from the table of the technical specifications or by weighing.

The weight of the structural installations (g_{5A}) is determined according to the installation blueprints of the units. It should take into account all the elements of the aircraft design, connected with installation of the given unit.

The weight of installation parts (g_{6A}) is determined according to the installation blueprints. In this case it is mandatory to take into account the increase in weight of the aircraft, caused by the presence of the installed electrical systems.

The weight of the d-c power system (g_{7A}) used for feeding the given consumer, is determined from the total weight of the d-c power system and the total power of all the consumers.

$$g_{7A} = \frac{G_{\bar{1}6c}}{\sum\limits_{i=1}^{n} P_i} \cdot P_k.$$

where $G_{16\varepsilon}$ - is the weight of the d-c power system. Index "16" indicates that the weight includes the first to the sixth elements of the weight. Analogous indices will be used later as well;

$\sum_{i=1}^{n} P_i$ - is the total capacity of direct current consumers including the short-time consumers;

n - is the number of direct current consumers;

P_k - is the capacity of the given consumer.

The weight of the a-c power system (g_{8A}), used for feeding this consumer, is determined analogously.

The additional weight of the aircraft (g_{9A}), caused by the installation of the electrical unit, depends on the type of the aircraft and may exceed the sum of all the other eight elements by 2 to 20 times.

From the first eight weight elements of the electrical unit the greatest in numerical value are the weights of the finished articles, wires and direct and alternating power systems, used for serving this electrical unit.

The above enumerated weight characteristics make it possible to determine the installed and flight weight of individual electrical units, the functions, and the entire complex of electrical equipment of an aircraft.

The weight of the electrical unit without taking into account the weight of the G_{16A} power system - is the sum of the first six elementary weights:

$$G_{16A} = g_{1A} + g_{2A} + g_{3A} + g_{4A} + g_{5A} + g_{6A}.$$

The weight of the electrical power system for the G_{78A} electric unit is determined by the sum of the seventh and eighth elementary weights:

$$G_{78A} = g_{7A} + g_{8A}.$$

The installation weight of the G_{18A} electrical unit is called the sum of the first eight elementary weights:

$$G_{18A} = G_{16A} + G_{78A}.$$

Depending on the type of electrical unit some component weights may be absent.

The installation weight of the electrical unit takes into account the increase of the weight caused by the service power systems.

The flight weight of the G_{19A} electrical unit is determined by the sum of the nine elementary weights according to the formula:

$$G_{19A} = G_{18A} + g_{9A}.$$

The flight weight of the electrical unit (system) in distinction from the installation "dead" weight takes into account all the additional weights, which are unavoidably related to the installation of this unit, and makes it possible to evaluate its actual "weight" for the aircraft.

Thus, for example, the flight weight of the generator may be determined as

$$G_{19A} = G_{18} + g_{9K} + g_{9T} + g_{9OX},$$

where G_{18} - is the installation weight of the generator;

g_{9K} - is the conditional weight of the aircraft structure caused by the installation of the generator;

g_{9T} - is the additional weight of the aircraft engine, fuel, lubrication, and structure of the aircraft, caused by drawing of the aircraft engine power for driving the generator. This weight depends on the characteristics of the aircraft engine with respect to fuel and lubrication consumption and the length of the flight;

g_{9OX} - is the weight of the generator cooling system dependent on velocity, altitude, and length of flight.

In particular, with a distant aircraft engine the equation for determining the flight weight of the generator assumes the following form:

$$G_{19} = (1 + \alpha + \beta + \gamma)\, G_{18} + (g + g_{f.lub}T)\frac{1.36\ P_r}{\eta_r \eta_{gr}} + g_{OX}T\ \frac{P_r}{\eta_r \eta_{gr}}\ (1 - \eta_r \eta_{gr}),$$

where: α - is the ratio between the weight of the aircraft structure caused by the increase of its elements upon the installation of the generator, to its "dead" weight;

β - is the ratio between the weights of the drive device of the generator to its "dead" weight;

γ - is the ratio between the weight of the cooling system of the generator to its "dead" weight;

g - is the weight of the aircraft engine per unit of power;

$g_{f.lub}$ - is the consumption of fuel and lubrication per unit of power of the aircraft engine per hour;

g_{OX} - is the consumption of the coolant of the unit of power of the generator per hour;

P_r - is the power of the generator in kW;

η_r - is the efficiency of the generator;

η_{gr} - is the efficiency of the drive-gear;

T - is the flight time in hours.

By the drive gear we understand a system of transmission of motion from the aircraft engine to the generator. For d-c generators and unstable frequency a-c generators this is a reducing gear, for stable frequency a-c generators this is a constant speed drive.

For jet engines the weight and consumption of fuel and lubricants are prescribed per unit of thrust. If the specific consumption for thrust is given the index of a dash, the equation for the flight weight of a generator assumed the following appearance

$$G_{19} = (1+\alpha+\beta+\gamma)G_{18} + (g' + g'_{f.lub}T)\ \frac{102\ P_r}{V\eta_r \eta_{gr}} + g_{OX}T\ \frac{P_r}{\eta_r \eta_{gr}}\ (1 - \eta_r \eta_{gr}),$$

where V - is the flight velocity in meters per sec.

The weights of the consumers, functions, and the entire complex of electrical equipment of an aircraft are determined analogously.

2. Determination of the Weight of Electrical Equipment.

According to the above introduced classification the weight of the electrical equipment of an aircraft is divided into four types: elemen-

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tary, total, installed (dead), and flight.

The concepts of each type of weight pertain in an equal measure to individual electrical units, functions, and the entire complex of electrical equipment of an aircraft.

For greater obviousness the sequence of calculation of the weight is presented in the diagram drawn in fig. 1.1.

In the calculation-system we give numbers from the first to the thirtieth with digital indices, indicating the elementary weights, included in the calculation. For example: 1_{16}, 3_{78}, 22_{19}, in which we include the elementary weights from 1 to 6; from 7 to 8; and from 1 to 9 included, respectively.

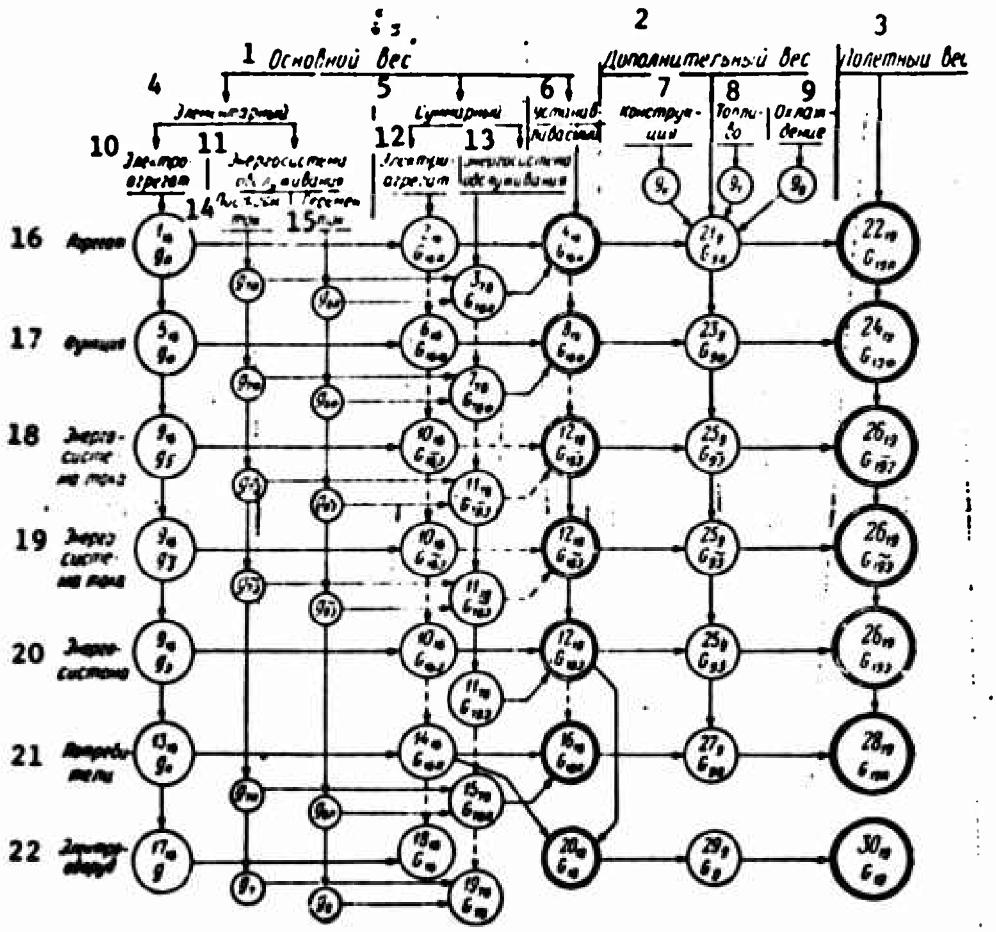

Fig. 1.1. Diagram of the Aircraft Electrical Equipment Weight Calculation.

Key: 1. Principal weight; 2. Additional weight; 3. Flight weight; 4. Elementary; 5. Summary; 6. Installed; 7. Structure; 8. Fuel; 9. Cooling; 10. Electrical unit; 11. Serive power system; 12. Electrical unit; 13. Service power system; 14. Direct current; 15. Alternating current; 16. Unit; 17. Function; 18. Current power system; 19. Current power system; 20. Power system; 21. Consumers; 22. Electrical equipment.

Letter g with the letter-digit index marks the elementary weights. For example: g_{5A} - is the fifth elementary weight of the assembly; $g_{1\varepsilon}$ - is the first elementary weight of the power system; g_{3n} - is the third elementary weight of the consumers.

The letter G with the corresponding index signifies the total installed and flight weights. The digital index indicates which elementary weights are included in the calculation, and the letters signify the type of equipment, for example: G_{16f} - is the total weight of the function; G_{18n} - is the installed weight of the consumers.

The numbers in combination with arrows indicate the order of calculation. The solid arrows show the most convenient order of calculation of the weight; the wavy arrows indicate the electric power assemblies, and the fine arrows the electric power systems for serving the electric power assemblies. For certain weights another order of calculation is possible which is indicated with a broken line.

In order to simplify the further calculations in the determination of the total, installed, and flight weights of electric units the latter should be grouped with respect to functions in accordance with the simplified circuit diagrams.

In the diagram we show the calculation of the weight for different variations of the feed of the consumers with direct and alternating currents. In actual practice the quantity of feed variations is limited and the calculation system is simplified considerably.

The flight weight of the electrical units, the functions, and the entire electrical equipment is the actual weight introduced into the aircraft upon the installation of the electrical units. The flight weight is the decisive factor in the comparison between the electrical equipment of various types of aircraft.

3. The Relative Weight of Electrical Equipment.

In the process of planning an aircraft, in order to select the lightest electric equipment system, a number of variations of individual electrical systems have to be worked out and compared with respect to their weight. However, by comparing the elementary, total, installed, and flight weights of electrical equipment we cannot determine the lightest electrical power system. Therefore, in order to make a comparative analysis of the weight of the electrical equipment of various systems, we introduce the concept of a relative weight, representing the ratio between the flight weight and the useful output of power of the assembly (system).

Thus, for example, the relative flight weight of an electrical system will be

$$\overset{*}{G}_{19A} = \frac{G_{19A}}{P_A},$$

where: P_A - is the useful output capacity of the electrical system.

The relative weights are subdivided into elementary, summary, installed, and flight weights, calculated for individual electrical units, functions, and the entire electrical equipment of an aircraft.

For a single type equipment of a similar capacity the relative weight is more conveniently determined for the entire set included in a function.

To determine the relative weight of a function we should proceed from the average relative weights of the basic electrical units, as the most accurate ones, ignoring in this case the relative weights of the secondary units, which have sharply expressed extreme values.

In this way, the relative flight weight is the principal criterion for the weight in the comparative evaluation of weights of individual elements and for the entire set of electrical equipment to various types of aircraft.

In the process of planning for the relative evaluation of weight of the electrical systems, it is quite useful to utilize approximate calculations of the relative installed weights.

In the approximate evaluation we performed a simple totaling up of the weights and their capacities.

1. The relative installed weight of an electrical unit

$$\overset{*}{G}_{18A} = \frac{G_{18A}}{P_A}.$$

2. Relative installed weight of the function

$$\overset{*}{G}_{18f} = \frac{G_{18f}}{P_f} \ .$$

where: G_{18f} - is the total weight of the function.

P_f - is the total output power of the function.

3. Relative installed weight of d-c electric power system

$$\overset{*}{G}^{-}_{18\varepsilon} = \frac{G^{-}_{18\varepsilon}}{P^{-}_{\varepsilon}} \ ,$$

where: $G^{-}_{18\varepsilon}$ - is the total weight of the d-c power system,

P^{-}_{ε} - is the total output capacity of the a-c power system.

4. The relative installed weight of the a-c power system

$$\overset{*}{G}^{\sim}_{18\varepsilon} = \frac{G^{\sim}_{18\varepsilon}}{P^{\sim}_{\varepsilon}} \ ,$$

where: $G^{\sim}_{18\varepsilon}$ - is the total weight of all the a-c power systems;

$P^{\sim}_{\varepsilon}$ - is the total output capacity of the a-c power system.

5. The relative installed weight of the power system

$$\overset{*}{G}_{18\varepsilon} = \frac{\overset{*}{G}^{-}_{18\varepsilon} + \overset{*}{G}^{\sim}_{18\varepsilon}}{2} \ .$$

6. The relative installed weight of the electric power consumers

$$\overset{*}{G}_{18p} = \frac{\sum_{1}^{n} \overset{*}{G}_{18p}}{n} \ ,$$

* the asterisk indicates relative weight.

where: $\sum_{1}^{n} G_{1\text{эр}}$ - is the total weight of the consumers of the function;

n - is the number of consumers in the function.

7. The relative installed weight of electrical equipment of an aircraft:

$$\overset{*}{G}_{1\text{э}} = \frac{\overset{*}{G}_{1\text{эс}} + \overset{*}{G}_{1\text{эр}}}{2}$$

Chapter 2. Reliability of the Electrical Equipment.

1. The Problem of Reliability of Electrical Equipment.

The problem of the reliability of the equipments' work attains special significance in connection with the fact that the development of the functions of electrical equipment proceeds in the direction from the auxiliary to the decisive function of control on the aircraft's flight.

The expansion of the range of problems, solved by means of electrical equipment, results in an abrupt complication of the latter, a mass employment of electronics, automations, and creation of complex systems of equipment.

In this connection, rigid limitations are imposed on the newly designed system on creation of a strengthened reserve (electrical, mechanical, and other) in connection with the necessity of obtaining systems with a minimum weight and volume.

In connection with the increase of speed of technical progress, the type permitted for developing new models is reduced sharply, which decreases the number of additional tests of different variations for a comparison of their reliabilities.

The growth of the speed of increased reliability falls behind and the requirements for it, which reduces the effectiveness of the new technological equipment, therefore the problem of reliability is the most important one in the processes of planning, production, and operation.

The electrical systems should be simple in operating-principle, reliable in operation, and viable under combat conditions.

On the rationality and correctness of the system and construction of installation of the electric power systems depends to a great ex-

* the asterisk indicates relative weight.

tent on their operational reliability and vitality.

All the consumers, with respect to their importance, are divided into three categories:

1. Consumers indispensable for flight. Their failure may result in great harm, catastrophy, or non-fulfillment of the assignment.
2. Consumers, the failures of which may cause a deterioration of the crew's working conditions, and complicate the flight conditions.
3. Consumers, operating only on the ground.

In order to assure complete safety and operational reliability the following demands are presented to the consumers of the first category:

1. The consumers should be supplied with feed under all conditions of the power system's work, including damage to individual units of the power supply lines.
2. The supply and systems control circuits should exclude the possibility of working conditions and controlled units situations inadmissible for flight safety, when the system fails or when there are troubles in the control or power supply lines.
3. In systems controlled by two or more members of the crew, a blocking system should be provided for, which would exclude the simultaneous switching on of the system for opposing motions (removal or extension, opening or closing, etc.) and assuring that the system would be controlled by only the principal member of the crew when they are simultaneously turned on by several members of the crew.

Principal Characteristics of an Aircraft's Electrical System's Reliability are:

Electrical Reliability. Presence of duplication and protection, correctness of selection of the switching equipment, and other elements of the system, absence of the harmful influence of some electric power consumers on the work of the others.

Safety of the System. Any failure of the system or erroneous action of the crew should not cause a direct emergency situation. Precise, immediate, and visual signalization of the failure of the system.

The visual nature and sufficiency of signalization of the position of the unit controlled. Presence of blocking systems and protective devices excluding accidental or incorrect switching on of the system. The failure of the blocking system should not disrupt the work of the principal control system.

Convenience in Operation. Simplicity of brief light inspection. Convenience of the use of controlling units in flight and the possibility of finding them rapidly. Reduction to a minimum of the possibility of erroneous operation in flight.

Possibility of rapid disconnection of the system controlled during an emergency situation.

Combat Vitality. Continuity of supply of power to the system upon damage to a part of the energy sources or part of the energy unit. Rapid and reliable disconnection of the damaged sector of the system.

2. Basic Concepts and Parameters in Calculating the Reliability.

In the mathematical calculations of reliability of electrical systems of aircraft the well-known general concepts, terms, and parameters are adopted which make it possible to analyze and evaluate the reliability of the different systems.

The system is the totality of the jointly acting technical devices, intended for carrying out specific functions.

Element of the system - is a part of the system, intended for carrying out specific functions.

Working order - is the state in which the system (element) at a given time-moment correspond to the technical specifications.

Working capacity - is the state in which the system (element) is capable at a given time-moment to carry out its functions with respect to the principal parameters, assuring flight safety.

Fault - is the state in which the system (element) at a given time moment does not respond to at least one of the established technical requirements.

"The basic fault" results in a failure, and "a secondary fault" does not cause a failure.

Failure - is the complete or partial loss of working capacity of a system (element).

Safety - is the property of the system (element) during the fulfillment of the prescribed functions under specific operational conditions and under the possible external actions, not to cause a breakdown of the aircraft or endanger the lives of the crew.

Reliability - is the property of the system (element) to retain its working capacity during a prescribed time interval under specific operating conditions.

Restorability - is the property of the system (element) to restore the working capacity as a result of elimination of the causes of the failure.

Non-Restorability - is the property of the system (element) not to be restorable after the origination of a failure.

Mean-time of a failure-free work - T_{cp} - of manufactured articles is the mean arithmetical time of their correct work.

For non-restorable articles the average failure-free worktime is determined as the ratio between the total accumulated working time of the articles which failed to their total number, that is,

$$T_{cp} = \frac{\sum_{i=1}^{N} t_i}{N},$$

where: t_i - is the accumulated working time of the article before appearance of the failure;
N - is the total number of the articles.

For restorable articles the average failure-free working time is determined in two stages: 1. The value of the average time $t_{i\ cp}$, accumulated between individual restorable failures of each article, is calculated as the ratio of the total working time of the article $\Sigma\Delta t$ to the total number of the failures n for this time, or ,

$$t_{i\ cp} = \frac{\sum \Delta t}{n},$$

where: Δt - is the time between successive failures of the article.

Thereupon, the mean-time of failure-free work of the entire number N of the articles is calculated:

$$T_{cp} = \frac{\sum_{i=1}^{N} t_{i\ cp}}{N}.$$

The average failure-free working time is an illustrative, quantitative reliability characteristic. It is convenient for evaluating the reliability of simplest elements, which after failure are not repaired. It may be used also for evaluating the reliability of complex devices, but in the latter case this characteristic will reflect the value of the meantime of failure-free work of a number of systems before their first failure.

Failure-Frequency - f - is the ratio between the number of articles, which have failed in a unit of time, and the initial number of the articles tested under the conditions, that all the articles out of order are not restored, i. e., the number of the articles tested during the testing period decreases (fig. 2.1):

$$f = \frac{\Delta N}{N_0 \Delta t} \quad ,$$

where: ΔN - is the number of articles which have failed during the time interval at Δt;

N_0 - is the initial number of the articles tested;

Δt - is the time interval.

According to the value of failure-frequency one can judge the number of the articles which may go out of commission during a described time-period, and determine the number of required reserve elements.

Failure-Intensity - λ (fig. 2.2) - is the ratio between the number of articles which failed during a time unit, and the mean number of articles which operated correctly during the given time period:

$$\lambda = \frac{\Delta N}{N \cdot \Delta t} = \frac{2\Delta N}{(N_1 + N_2)\ \Delta t} \ ;$$

where: Δt - is the working time;

N_1 - is the number of articles operating correctly at the beginning of the time period Δt;

N_2 - is the number of articles operating correctly at the end of the Δt time period;

N - is the number of articles operating correctly during time Δt;

ΔN - is the number of articles which have failed during the time Δt period.

Fig. 2.1. Typical Curve of a Variation of Equipment Failure Frequency according to the operation stages.

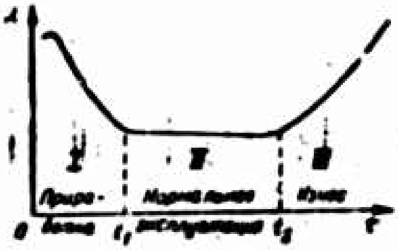

Fig. 2.2. Typical Curve of a Variation of the Intensity of Equipment Failure according to the stages of operation.

Key: I. Working-in period; II. Normal operation; III. Wear.

In the time interval between 0 to t_1 the intensity of failures decreases sharply. In this sector the elements are waiting in and go out of commission through internal faults. In the sector from t_1 to t_2 the intensity of failures for the majority of elements is a constant value. This sector characterizes the normal work of the elements. The growth of the failure intensity curve upon the passage of time t_2 is explained by the mechanical and electrical wear of the elements.

The intensity of the articles' failures characterizes the most complete reliability of the elements and is one of the best reliability characteristics.

Since it is considered, that all the elements in the equipment operate during the period of normal operation, that is, the periods of waiting in and wear, are not examined, the values of the failure intensity are given in the form of a constant value per one working hour.

The tentative data on the intensity of failures of various electrical equipment elements in aircraft are given in Table 2.1.

According to the failure intensity value we can judge on the quality of the elements; the higher the quality the higher is the reliability and the smaller is the value of failure intensity.

The failure intensity of a given single type element operating under a similar regime and identical surrounding conditions may fluctuate within a wide range. Its value depends on the quality of the materials, technology, and efficiency of production, complexity of the elements, etc.

Table 2.1. Tentative Data of Failure-Intensity of Electrical Equipment Elements

1 Наименование элементов	2 Интенсивность отказов на 1 час работы	3 Наименование элементов	4 Интенсивность отказов на 1 час работы
5 Сопротивления	$(0,001 \div 1,5) 10^{-5}$	22 Трансформаторы мощные	$(0,02 \div 0,2) 10^{-5}$
6 Конденсаторы	$(0,001 \div 16,4) 10^{-5}$	23 Индуктивности, дроссели	$(0,002 \div 4,4) 10^{-5}$
7 Потенциометры	$(0,5 \div 13,1) 10^{-5}$	24 Соленоиды	$0,5 \cdot 10^{-5}$
8 Электровакуумные приборы	$(0,1 \div 31,5) 10^{-5}$	25 Соединения штепсельные	$(0,001 \div 9,1) 10^{-5}$
9 Полупроводниковые диоды	$(0,012 \div 50) 10^{-5}$	26 Соединения пайкой	$(0,01 \div 1) 10^{-5}$
10 Полупроводниковые триоды	$(0,02 \div 90) 10^{-5}$	27 Измерительные приборы	$(0,5 \div 6) 10^{-5}$
11 Реле	$(0,05 \div 101) 10^{-5}$	28 Индикаторные лампы	$(0,01 \div 0,3) 10^{-5}$
12 Переключатели	$(0,0043 \div 2,8) 10^{-5}$	29 Датчик давления, температуры	$(0,15 \div 6,6) 10^{-5}$
13 Выключатели, кнопки	$(0,01 \div 1,2) 10^{-5}$	30 Электродвигатели маломощные	$(0,015 \div 33) 10^{-5}$
14 Микровыключатели	$26,2 \cdot 10^{-5}$	31 Электродвигатели силовые	$(0,035 \div 0,2) 10^{-5}$
15 Пускатели	$(1,2 \div 7,5) 10^{-5}$	32 Муфты электромагнитные	$(0,043 \div 9,4) 10^{-5}$
16 Автоматы защиты	$10,2 \cdot 10^{-5}$	33 Преобразователи	$(25 \div 100) 10^{-5}$
17 Инерционные предохранители	$5 \cdot 10^{-5}$	34 Генераторы	$(20 \div 100) 10^{-5}$
18 Плавкие предохранители	$1 \cdot 10^{-5}$	35 Генераторы бесконтактные	$(0,8 \div 5) 10^{-5}$
19 Магнитные усилители	$(0,02 \div 0,5) 10^{-5}$	36 Аккумуляторные батареи	$(50 \div 100) 10^{-5}$
20 Электрические фильтры	$0,3 \cdot 10^{-5}$		
21 Трансформаторы малой мощности	$(0,002 \div 6,63) 10^{-5}$		

1. Name of elements
2. Failure-intensity per 1 out of work
3. Name of elements for failure-intensity per 1 out of work
4. Failure-intensity per 1 out of work
5. Resistors
6. Capacitors
7. Potentiometers
8. Electrical vacuum instruments
9. Semi-conductor diodes

10. Semi-conductor triodes
11. Relays
12. Two-way switches
13. Switches, buttons
14. Microswitches
15. Starters
16. Protective automatic devices
17. Inertial cathodes
18. Fuses
19. Magnetic amplifiers
20. Electrical filters
21. Low power transformers
22. High power transformers
23. Induction, choke coils
24. Solenoids
25. Plug connections
26. Solder connections
27. Measuring instruments
28. Indicator lamps
29. Pressure and temperature sensors
30. Low power electric motors
31. High power electric motors
32. Electro-magnetic clutches
33. Transformers
34. Generators
35. Conductless generators
36. Storage batteries.

Today, the data on failure intensity of various elements (Table 2.1), have as a rule, a generalized character without indication of specific conditions, for which they are correct, and may be used only in approximate calculations.

Probability of Failure-Free Work - P - is the probablity of the fact that under specific operating conditions within the boundaries of the prescribed time period no failures occur in the work of the article (fig. 2.3). The probability of failure free work is the principal reliability characteristic.

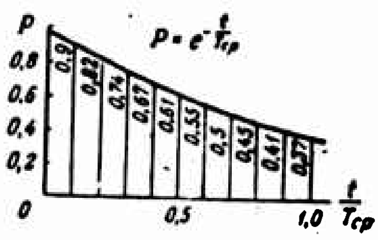

Fig. 2.3. - Typical Variation of Failure-free Work Probability in Time.

In the general case, when there is a complex relationship between the frequency or intensity of failures and time, value P may be calculated with the formula:

$$P = e^{-\int_0^t \lambda(t)dt} .$$

For certain elements (system) the series of failures may be practically considered as the simplest series of random events, subject to Poisson's law, in the opposite case during a period of normal operation the intensity of the articles' failures does not depend on time and is a practically constant value (λ = const) and then the probable reliability is determined according to the exponential law of reliability:

$$P = e^{-\lambda t} = e^{-\frac{t}{T_{cp}}} ,$$

where: t - is the prescribed working time.

The exponential law of reliability is correct, when the mechanical or electrical wear of the elements has not yet practically arrived, while the waiting in period has been completed, i. e., it is correct for the period of the normal work of the elements.

The exponential law of reliability is correct for the majority of simple electrical systems. It is also used in calculating complex systems, consisting of a large number of elements, the variation in the reliability of which differs from the exponent, and the mean time periods of satisfactory work differ. This case is typical for the majority of complex systems. Practical experience shows that calculations of probability of satisfactory work, carried out under the exponential law of reliability, in many cases agree well with the exponential data.

From the exponential law of reliability (see fig. 2.3) follow the next important conclusions:

1. Reliability of the complex system, as an element, agrees with the course of time to the exponential law.
2. The more complex the system (non-reserved) i. e., the greater the number of elements included in it, the lower is its reliability.
3. The reliability of the system depends to a great extent on the reliability of the elements of which it consists.
4. If durirg a prescribed working time there is the possibility of appearance oi a single failure, i. e., $t_p = T_{cp}$, the probability of failure-free work will be of the order of 0.37.
5. If a failure-free work exceeds by ten times the prescribed working time, i. e., $t_p = 0.1\ T_{cp}$, the probability of failure-free work of an article will be not greater than 0.9.

Thus, in order to assure a higher level of failure-free work probability, it is necessary to increase substantially the mean time of failure-free work in comparison with the prescribed working time of the article.

The reliability of a system may be increased by simplifying it and increasing the reliability of its component elements. However, the decrease of the number of elements in this system, and the increase of their reliability, is a complex technical problem.

The exponential law of reliability is inapplicable for the initial period of the work of the system, when the process of waiting in takes place and the intensity of failures is not a constant value.

The introduction into the exponential law formula of an additional, factor K, obtained from statistics, may take into account the tact of the correct work of the system of a failure during the waiting in period and other factors.

3. Brief Information on the Theory of Probabilities as applied to the Calculation of Reliability.

The theory of probability studies the mass cases of an event or processes, possessing stable frequency of appearance.

Upon an unlimited increase of the number of tests the statistical values of the frequency approaches (converges with respect to probability) to a certain number called THE PROBABILITY OF A GIVEN EVENT:

1. If during a given test the realization of one of the events examined A_1, $A_2 \ldots A_n$ does not prevent the realization of any other one of them, the events are called compatible. In this case the events will be independent, if the appearance of one of them will not change the probability of the appearance of another.

For compatible events the theory of multiplication of probability is applicable, which is written for independent events in the following form:

$$P(A_1 \cdot A_2 \ldots A_n) = P(A_1) \cdot P(A_2) \ldots P(A_n).$$

2. If during the given test only one of the conditions examined A_1, $A_2 \ldots A_n$, may occur. These events are called incompatible.

For incompatible events the theory of addition of the probabilities is applicable:

$$P(A_1+A_2+\ldots+A_n) = P(A_1) + P(A_2) + \ldots + P(A_n).$$

The events, included in the working state of the system (element) and in its failures, are incompatible, since the system cannot work and work at the same time. In this case in the theory of probabilities it is said, that incompatible events form a full group for which

$$P + Q = 1,$$

where: P - is the probability of the fact that the system will be workable;

Q - is the probability of the opposite event (failure of the system).

In the general case for the full group of events $A_1, A_2 \ldots A_n$

$$\sum_{i=1}^{n} P(A_i)=1.$$

<u>In the theory of reliability we distinguish three basic conventional types of combinations of systems (elements): successive, parallel, and mixed.</u>

In the practice of calculation of the reliability of the system <u>the method of structural systems</u> has become widely popular. The calculation system according to this method is formed on the basis of successive and parallel connection of the elements included in a given system. These types of conventional connections used for the calculation system of reliability do not always coincide with designed connection of the elements in the system, i. e., the parallel connection of certain elements in the electrical circuits in the calculation of reliability in a number of cases may be a series connection.

A series connection (basic) is called the totality of systems (elements) for which the necessary and sufficient condition for a failure is the failure of even one (any) system (element) included in the given totality. The calculation system and the dependence of the system's reliability on the reliability of its elements in a series connection are given in fig. 2.4.

According to the theory of multiplication of probabilities under the condition, that the failure of each of the n elements of its system is an independent event, we obtain

$$P = P_1 \cdot P_2 \ldots P_n,$$

where: P - is the probable reliability of the system;
$P_1, P_2 \ldots P_n$ - is the probable reliability of individual elements.

If the reliability of all the elements is approximately equal, then

$$P = P_1^n.$$

Evidently, for the system consisting of n types of elements with the probability of correct work $P_1, P_2 \ldots P_n$, and the number of elements $n_1, n_2 \ldots n_n$ may be written as

$$P = P_1^{n_1} P_2^{n_2} \ldots P_n^{n_n}.$$

To obtain high reliability of the system with series connection of the elements, the elements included in it should possess a very high degree of reliability, since the failure of one element signifies the failure of the entire system.

Fig. 1.6. Dependence of reliability of a system on the reliability and number of elements connected in series: 1, 2, 3 n - is the number of elements.
Key: 1. Calculation diagram. 2. Reliability of system P. 3. Reliability of element P_1.

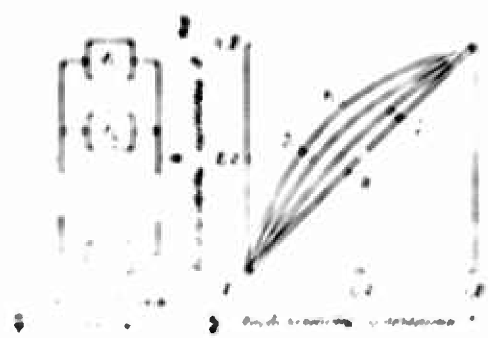

Fig. 1.7. Dependence of the system's reliability on the reliability and number of elements connected in parallel: 1, 2, 3, 4 - is the number of elements.
Key: 1. Calculation diagram 2. Reliability of system P. 3. Reliability of element P_1.

Examples: 1. The system consists of three types of elements ($m=3$), possessing specific probabilities of good working orders, i. e., $P_1 = 0.995$, $n_1 = 40$; $P_2 = 0.995$, $n_2 = 40$; $P_3 = 0.985$, $n_3 = 10$.

Then the probability of failure free work of the system is

$$P = 0.995^{40} \cdot 0.995^{40} \cdot 0.985^{10} = 0.82 \cdot 0.82 \cdot 0.87 = 0.58.$$

2. The system consists of 100 elements connected in series.

Determine the mean probability of failure free work of the elements providing for a probability of good working order of the system equal to 0.9.

$$P = 0.9 = P_i^{100}.$$

$$P_i = 0.9981.$$

A parallel connection is the totality of systems (elements) for which the necessary and sufficient conditions for a failure is the failure of all the systems (elements) included in the totality.

The calculation system and dependence of the reliability of the system on the reliability of its elements connected in parallel is given in fig. 2.5.

The probability of failure of system Q with the elements connected in parallel is equal to the product of the probabilities of failures of the component elements:

$$Q = \prod_{j=1}^{k} q_j = \prod_{j=1}^{k} (1 - P_j),$$

where: q_j - is the probability of failure of the j element,

P_j - is the probability of good working order of the j element,

k - is the number of elements working in parallel

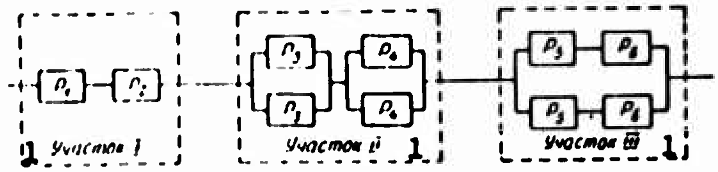

Fig. 2.6. Diagram of calculation of the reliability of the system with mixed connection of the elements.
Key: 1. Sector or section.

The system with a parallel connection of the elements will not go out of commission until all its elements have failed.

The probable reliability of system P in this case is determined as follows:

$$P = 1 - Q = 1 - \prod_{j=1}^{k} (1 - Pj).$$

Since the usual elements connected in parallel (reserve) are equally reliable, then

$$P = 1 - (1 - Pj)^k.$$

Example. The system has k = 3, Pj = 0.9. Determine P

$$P = 1 - (1-0.9)^3 = 1-0.1^3 = 0.999.$$

Parallel connections of subsystems (elements) should be used when the reliability of the system should be higher than the reliability of the subsystems (elements).

A mixed connection is a set of systems (elements) in which various combinations of series and parallel connections of both the individual elements (units) and systems are used.

In Fig. 2.6 we present one of the possible systems of calculation of the reliability of a system with mixed connection. In sector I the elements are connected in series, its reliability is determined as $P_I = P_1 \cdot P_2$.

In sector II the elements are connected in parallel-series, its reliability is determined as follows:

$$P_{II} = [1-(1-P_3)^k] \cdot [1-(1-P_4)^k] \text{ when } P_3 = P_4,$$

$$P_{II} = [1-(1-P_3)^k]^n.$$

In sector III the elements are connected in series-parallel, its reliability is determined as follows

$$P_{III} = 1 -(1-P_5 \cdot P_6)^k.$$

The sectors are connected with one another in series, therefore, the reliability of the system is determined as the product of the reliabilities of individual sectors of the system

$$P = P_I \cdot P_{II} \cdot P_{III} = \prod_{i=1}^{n} P_i.$$

Example. Determine the reliability of a system the elements of which are connected as it is shown in fig. 2.6 and have the probable work reliability equal to $P_1 = P_2 = 0.97$; $P_3 = P_4 = 0.8$; $P_5 = 0.9$; $P_6 = 0.95$.

$$P_I = P_1 \cdot P_2 = 0.97 \cdot 0.97 = 0.94;$$

$$P_{II} = [1-(1-P_3)^k]\cdot[1-(1-P_4)^k]=[1-(1-0.8)^2]^2 = 0.92;$$

$$P_{III} = 1-(1-P_5 \cdot P_6)^k = 1-(1-0.9 \cdot 0.95)^2 = 0.98;$$

$$P=P_I \cdot P_{II} \cdot P_{III} = 0.94\cdot 0.92\cdot 0.98=0.848.$$

The method of structural systems is simple and convenient, i. e., when the element of the system is subject to only one type of failure. In a complex system, when the element is subject to two different types of failure, the method of structural system is not always applicable. For such instances the most universal is the method of failure free work diagrams developed on the basis of the algebra of logic.

Let us examine the essence of that method using an example-problem on the selection of the most reliable type of connection (series or parallel) of two identical semiconductor diodes, each of which is subject to two different types of failures' to be punctured or torn. In fig. 2.7 we show two possible simplified diagrams of connections of the diodes: in series and in parallel.

It is prescribed, that the diodes may fail because of puncture with the probability of $q'_d = 0.040$ and there with $q''_d = 0.030$. The probability of failure of the other two conventional elements, included in the systems in parallel with the diodes, is assumed to be equal to $q = 0.001$.

The prescribed probabilities of failure free work and failures of the component elements in this case will be:

1 Безотказной работы			2 Отказа	
$P = 0{,}999$			$q = 0{,}001$	
$P_d = 0{,}930$			$q_d = 0{,}070$	
$P'_d = 0{,}960$	$[P_d + q'_d + q''_d = 1]$		$q'_d = 0{,}040$	по пробою 3
$P''_d = 0{,}970$			$q''_d = 0{,}030$	по обрыву 4

Key: 1. Failure free work; 2. failure; 3. because of puncture; 4. because of rupture.

Let us form a diagram and equations for calculating the probabilities of failure free work of bus-systems

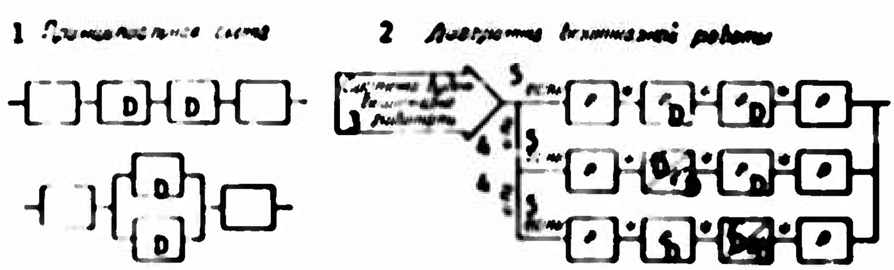

Fig. 2.7. Calculation diagram for failure free work.
Key: 1. Simplified diagram; 2. failure free work diagram; 3. system will work without fail; 4. or, or; 5. if, if, if.

The basic method for construction of the failure free work diagram is the compilation of a chain of logical conditions, determining those combinations of interrelated actions of individual elements of a system, with which failure free work is assured. These logical conditions are written in the form of a diagram and algebraic equation of events, determining the failure free work of a system, by means of elementary logic algebra functions: logical multiplications, additions.

and negations of events. The replacement of events by the values of probability and their appearance results in an expression for calculating the probability of failure free work of the entire system.

In the problem examined, the diagram consists of three logical chains (conditions) of failure free work:

1) Diagram of diodes connected in series - all elements of the system work without fail; - failure through puncture (q'_d) of one of the diodes under the condition of failure free work of the other elements of the system. This logical conclusion is reflected in the diagram in the form of two analogous chains.

2) System of diodes connected in parallel - all elements of the system work without fail; - failure through rupture (q''_d) of one of the diodes under the condition of failure free work of the other elements of the system.

In the diagram we show two analogous logical chains expressing this condition.

The probability of failure free work of two diodes on the basis of the initial data adopted for a series and parallel connection are determined by the following formulas:

$$P_{series} = P^2 \cdot P_d^2 + P^2 \cdot q'_d \cdot P_d + P^2 \cdot P_d \cdot q'_d = P^2 \left(P_d^{''2} - q_d^{'2}\right) =$$

$$= 0.999^2 \left(0.970^2 - 0.040^2\right) = 0.938;$$

$$P_{parallel} = P^2 \cdot P_d^2 + P^2 q''_d \cdot P_d + P^2 \cdot P_d \cdot q''_d = P^2 \left(P_d^{'2} - q_d^{''2}\right) =$$

$$= 0.999^2 \left(0.960^2 - 0.030^2\right) = 0.920.$$

In this way, in this case the reservation of two diodes by their parallel connections is less reliable, than with series connections.

4. Ways to Increase Reliability.

Measures for increasing reliability may be taken in planning, production, in operation of systems (elements).

Usually the cost of operational systems (elements) exceeds substantially the cost of planning and production, therefore the principal effort should be directed towards the creation of reliable systems and elements. Nevertheless, in the field of operation also, important measures may be taken for increasing the reliability.

In the course of planning the reliabilities of systems (elements) may be attained both by the system and the design methods.

System Methods raise the reliability of systems (elements) improving their simplified diagrams, namely:

1. Creating the simplest diagrams possible.
2. Creating diagrams with eliminated consequences of failures.
3. Reserving elements and systems.
4. Introducing automatic control.

Diagram methods are one of the decisive factors in creating reliable elements and systems and when they are skillfully used, they make it possible to obtain reliable systems, even with insufficient reliable elements.

Creation of the Simplest Systems possible is one of the most important and difficult problems in planning the systems.

One of the causes of origination of the reliability problem is the complexity of diagrams of modern systems, and therefore the rationale in degrees of the number of elements in a system (without harmful characteristics and functioning) is the determing factor in their planning process. For relay-contact systems a theory based on logic algebra exists, which makes it possible to plan complex problems with a minimum required number of relay-contact elements. The degrees of the complexity of the systems is the only method with which the increase of reliability accompanies the degrees of weight and volume of the system.

Creation of Systems with Limited Failure Results - is of great importance for avaiation systems of a responsible purpose (power systems, control systems, and so forth). Failures of such systems are divided into two groups:

1. Failures with dangerous consequences; disruption of the flight assignment, forced landing, accident, catastrophy.
2. Failures without dangerous consequences; the deterioration of working conditions for the crew, complication of flight conditions, reduction of comfort, and so forth.

The systems, carrying out the reliable functions of aviation systems, should be built in such a way as to exclude the possibility of appearance of failures with dangerous consequences, or at least to increase the values of the consequences on the appearance of a failure of the systems or its elements and sectors.

In powersystems the appearance of a dangerous consequence is also connected with the loss of feed for a number of systems and a possible catastrophy.

Analogous consideration may be expressed with respect to the system of autamation of aircraft engines, automatic pilot, and other systems, used in the aircraft (especially pilotless aircraft).

Reservation - is the most effective and promising systems method of increasing the reliability of elements and systems.

Among the design methods of increasing the reliability of the systems applied are methods, analogous to those examined for the systems (creation of the simplest possible design, creation of designs with eliminated failure consequences, and reservation of structural elements), and also auxiliary measures: creation of reliable elements, correct selctions of their parameters, and favorable working conditions, standardization of elements and systems, convenience in operation and repairs.

The reliability of an element is determined primarily by the principle of its operation, and also depends on its design method and condition of use. Usually the most reliable are the elements which have no moving parts, incandescent filaments, and fine windings. In this connection semi-conductor elements are very promising.

New design elements should be unified and possess a high characteristic of uniformity during the good working order period.

New design development are based to a great extent on a series produced structural elements, therefore, their reliability should improve continuously.

Elements should be used only under working conditions specified in the technical specifications, since the excess of electrical, trouble, infiltration loads, raises substantial (up to tens of times) the intensity of their failure.

In planning the systems we should take into account the changes in the parameters of the materials and parts with time and provide for the possibility of repairs in the process of operation. A comprehensive automatic control system should provide control of the working order of the systems and warnings on the place of failure-origination. In this case the built-in control elements should not reduce the reliability of the principal system.

In the process of production the reliability may be increased in the following directions:

1. Improvement of the production processes.
2. Automation of production.

3. Draining of the elements and systems.
4. Control of product quality.
5. On the ground adjustment of natural size mock-ups of electrical systems with imitation of emergency conditions.

In the process of operation the increase of reliability may be provided for by:

1. Strict adherence to instructions on operation, regulation, and their operations.
2. Extensive use of semi-automatic and automatic control of systems on the ground and in flight with forecasting of failures.
3. Collection and processing of statistical data on the experience in operation of the systems.
4. Communications with the industry and planning organizations.

In many cases the methods of servicing is an indispensable means for maintaining the reliablity of electrical systems and their elements at the appropriate level.

5. Methods and Ways of Reservation.

The increase of the quality of the system by means of rational use of excess elements is called reservation. The system shall be called reserved, if upon a failure of one of several elements it continues to function normally. A reservation may be performed by two methods: "hot" or "cold" reserve, which differ with respect to the action of the system to appearance of failure.

"Hot"-reserve is the constant inclusion of reserve elements parallel to the principal one under normal working conditions. Upon the origination of failures there is no disruption in the work of this system until at least one of the parallel connected elements is in good working order.

This method is simple, economical, and reliable, especially when elements, small units and their feed-lines are reserved. Since the elements are permanently connected, it is not required to have switch-over devices or failure-signalization devices.

With the "cold"-reserve the reserve elements are in a disconnected state (it is assumed, that the intensity of the failures under this condition is equal to 0). The next reserve element is included in the work, after the one which has been working has gone out of order.

Short-comings of this method:

1. Disruption in the work of the system from the moment of failure of the working elements until the connection of the reserve went into

operation. This phenomenon is especially dangerous in the electric power supply system.

2. The necessity of having switch-over devices and working-devices, which increases the volume, weight, and cost, and reduces the reliability.

Both reservation methods may be used with different methods of connection of the reserve elements or circuits.

There are two principal methods of reservation: the general and the separate.

General Reservation consists of reservation of the entire system as a whole. Thanks to its simplicity this method has become widely popularized especially in the secondary power systems with transformers of direct current into alternating, and alternating into direct current.

Separate Reservation consists of reservation of a system according to individual sectors or elements. Any division of the reserve i o smaller items (reservation on a smaller scale) is more advantageous from the point of view of increasing the reliability of the system. An example of this may be a parallel connection into the feed-network of the generator feeders by individual sectors of the feed-line, to channel feed and control important consumers, etc.

In designing conduct elements we may use internal reservations, i.e., independent switch-rods, regulating their independent conducts, independent conducts of the basic relay with independent control windings and so forth.

Use of the above mentioned ways and methods of reservation in the primary and secondary powersystems are examined in the corresponding sections.

However, the reserve connection of the system (elements) is not only sufficiently effective. This pertains to cases when the same element of a system is subjected to several failures which differ in their physical essence. In this case for a single type of failures in order to provide for reservation, the element has to be connected into the structural system in series, another type of failures in parallel series. In such cases, each of the above mentioned connections by itself may provide only partial reservation. Energy about this is provided by examples given in Table 2.2.

In such cases the use of systems, consisting of combinations of series and parallel connections for calculating the reliability becomes practically inconvenient. In this case it is advisable to carry out the calculations on the basis of logic algebra methods.

Table 2.2.

1 Элемент	2 Характер отказа	3 Схема включения, исходя из резервируемости отказа
4 Полупроводниковый диод	5 Короткое замыкание	6 Последовательное
	7 Обрыв	8 Параллельное
9 Электромеханизм системы управления	10 Ложный плюс	11 Последовательное
	12 Обрыв цепи управления	13 Параллельное

1. Element
2. Nature of failure
3. Connection system proceeding from the failure reservation
4. Semi-conductor diode
5. Short-circuit
6. Series
7. Rupture
8. Parallel
9. Control system electric mechanism
10. False pole
11. Series
12. Rupture of control circuit
13. Parallel

Very reliable systems and elements may be created by using reservations. With the optimum diagrams for certain systems this does not cause a substantial increase in weight and volumes, especially in connection with extensive use of small dimension semiconductive instruments and their super-miniature parts.

The continuous growth of complexity of diagrams of modern systems increases the demands for the reliability of elements, however, it is extremely difficult to reduce the intensity of element-failure to a minimum value through design and production measures in a short period of time, and therefore reservation at a given stage is one of the essential methods for increasing reliability.

6. Tentative Calculation of Power System Reliability.

Tentative calculation of the reliability of power systems is carried out at the stage of rough draft in the development of the simplified circuit diagram. In this case it is assumed that:

1. All the elements operate during a normal period of time under normal conditions, their number, type, and failure intensity are known.
2. The entire system functions during the maximum time of a single flight.
3. At the moment of start of functioning the system is in good working order which is achieved bv the corresponding control.
4. Failures of the elements in time are distributed according to the exponential law, that is, the probability of failure free work of an element is determined through and according to formula

$$P = e^{-\lambda_i t_i},$$

where λ_i - is the mean intensity of failures of the i element;

t_i - is the working time of the i element.

The calculation probability of power systems is carried out in the following sequence;

1. We determine the probability of failure-free work P of the included units, auxiliary elements and wires for the prescribed maximum time flight i, in this case the intensity of failures is selected according to the statistical data of operation of analogous equipment:

$$P = e^{-\lambda t}.$$

2. The probability of failure-free work of a single channel (generator with equipment) of power P_K is determined as the product of probability of failure-free work of the corresponding units

$$P_K = P_1 \cdot P_2 \ldots P_n.$$

3. The probability of safe work of electrical power systems is determined by the probable safety of the work of the channels included.

The reliability of a system of electrical power supply is examined in the sense of providing flight safety. By flight safety we understand the probability of the power system for its possible external damage to provide feed to the consumer, on the work on which depends the life of the participants in the flight and the performance of the assignment. The disruption of safety results in a dangerous situation.

In the power system with parallel operating channels, the n time-duplication is provided for, therefore simultaneous going-out of commission of n-1 channels does not result in the failure in the feed of the principal consumers, if the available power of one channel is sufficient. The dangerous situation begins only when all the n channels go out of commission.

The probability of safe work of a power system P_c (presence of feed at the main distribution busses) in this case is determined by the expression

$$P_c = 1 - Q_c = 1 - Q_K^n = 1 - (1 - P_K)^n.$$

A single failure in one of the channels does not result in the appearance of a dangerous situation. However, depending on the character of a failure (i. e., short circuit at the central busbar) and the system of unification of channels into parallel work, the dangerous situation may appear in this case also. A dangerous situation may originate also in the case of double failures during certain combinations. For example, the failure of an element in the voltage regulation system and failure of an element in the corresponding protection device. In certain power systems the break-down or wa[illegible] of generator bearings also results in a dangerous situation. In this case, due to the rigid connection of the generators with the aircraft engine, the mechanical friction of the parts of the generators may cause a fire in the aircraft.

The probability of origination of failure of a system $Q_{o.c}$, caused by a certain double-failure of the units, is determined as

$$Q_{o.c} = Q_1 \cdot Q_2 ,$$

where, for example Q_1 - is the probability of appearance of a failure in the voltage regulator unit;

Q_2 - is the probability of appearance of a failure in the protection unit.

The fear of double-failures, resulting in a dangerous situation, is determined by the proportion

$$\beta = \frac{Q_{o.c}}{Q_K} = \frac{Q_{o.c}}{1-P_K}.$$

The probability of the absence of a dangerous situation for the n-channel system of the electrical power supply is determined by the formula

$$P_C = (1 - \beta Q_K)^n - (1 - \beta)^n Q_K^n,$$

where Q_K - is the probability of failure of one of the n-channels;

βQ_K - is the probability of double failure resulting in a dangerous situation.

According to the calculation of reliability of an electric power system the composition and types of the elements, the regimes of their work and the diagrams of connections are rendered more precise and the optimum variation of the simplified diagram of the electric power system is finally determined.

Let us examine examples of tentative calculations of reliability of electrical power systems for direct and alternating current.

Example 1*. Calculation of reliability of a d-c power system.

Calculation of reliability of a generator's feeder. The calculation system of a generator's feeder, shown in fig. 2.8, consist of a series connection of elements. If from statistics we know the intensity of a failure of elements, using the exponential law, we may determine the reliability.

1. Cutout 1, $\lambda_1 = 0.01 \cdot 10^{-3}$.

$$P_1 = e^{-\lambda_1 t} = 2.73^{-t} \cdot 0.01 \cdot 10^{-3}.$$

2. DMR: relay 6 pieces, $\lambda_{21} = 0.02 \cdot 10^{-3}$; soldered connections 35 pieces, $\lambda_{22} = 0.0001 \times 10^{-3}$; plug connections 7 pieces, $\lambda_{23} = 0.0005 \cdot 10^{-3}$.
The elements are connected in series.

* The double failure in a single channel resulting in a dangerous situation, is not examined in this example.

$$P_{\cdot} = e^{-t(6\cdot 0.02+35 \cdot 0.0001+7 \cdot 0.0005) \cdot 10^{-3}} = 2.73^{-t \cdot 0.127 \cdot 10^{-3}}.$$

3. Switch 1 piece, $\lambda_3 = 0.01 \cdot 10^{-3}$.

$$P_3 = e^{-t \cdot 0.01 \cdot 10^{-3}}$$

4. Voltage regulator; carbon rod 1 piece, $\lambda_{41} = 0.08 \cdot 10^{-3}$, resistor 4 pieces, $\lambda_{42} = 0.01 \cdot 10^{-3}$, rectifier 4 pieces, $\lambda_{43} = 0.01 \cdot 10^{-3}$, electric magnet windings 4 pieces, $\lambda_{44} = 0.0015 \cdot 10^{-3}$, soldered connections 25 pieces, $\lambda_{45} = 0.0001 \cdot 10^{-3}$, plug connections 5 pieces, $\lambda_{46} = 0.0005 \cdot 10^{-3}$.

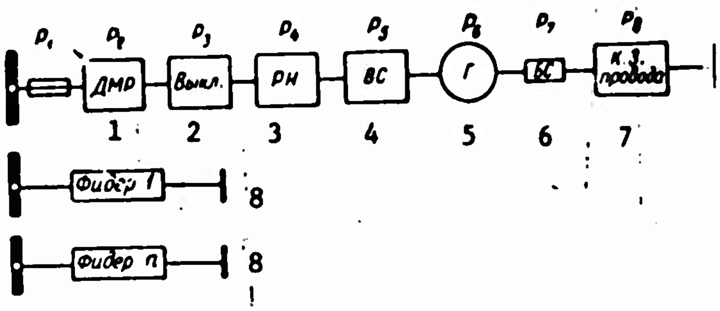

Fig. 2.8. Diagram of calculation of generator-feeder reliability. Key: 1. DMR, 2. Switch, 3. Voltage regulator, 4. Outside resistor, 5. Generator, 6. Ballast resistor, 7. Short circuit wires, 8. Feeder.

The elements are connected in series.

$$P_4 = e^{-t(0.08+4 \cdot 0.01+4 \cdot 0.01+4 \cdot 0.0015+25 \cdot 0.0001+5 \cdot 0.0005) \cdot 10^{-3}}.$$

$$P_4 = e^{-t \cdot 0.171 \cdot 10^{-3}}.$$

5. Outside resistance $\lambda_5 = 0.12 \cdot 10^{-3}$.

$$P_5 = e^{-t \cdot 0.12 \cdot 10^{-3}}.$$

6. Generator 1 piece, $\lambda_6 = 0.2 \cdot 10^{-3}$.

$$P_6 = e^{-t \cdot 0.2 \cdot 10^{-3}}.$$

7. Ballast resistance 1 piece, $\lambda_7 = 0.001 \cdot 10^{-3}$.

$$P_7 = e^{-t \cdot 0.001 \cdot 10^{-3}}.$$

8. Short circuit. Length 5 m, $\lambda_8 = 0.0001 \cdot 10^{-3}$ length 1 m.

$$P_8 = e^{-t \cdot 5 \cdot 0.0001 \cdot 10^{-3}} = e^{-t \cdot 0.0005 \cdot 10^{-3}}.$$

The reliability of the generator feeder is determined by the product of reliability of the elements included.

$$P_K = P_{18} = P_1 P_2 \cdot P_3 \cdot P_4 \cdot P_5 \cdot P_6 \cdot P_7 \cdot P_8 =$$

$$= e^{-t(0.01+0.127+0.01+0.171+0.12+0.2+0.001+0.0005) \cdot 10^{-3}}$$

$$P_K = e^{-t \cdot 0.6395 \cdot 10^{-3}}.$$

In this way the probable reliability is determined: for 10 hours of work $P_K = 0.9931$. For 200 hours of work $P_K = 0.7447$. With parallel connections of engine readings into the network. The reliability of the power supply is determined by the expression

$$P_c = 1 - (1 - P_K)^n.$$

For example, when n = 2.
In 10 hours of work $P_c = 1-(1-09931)^2 = 0.9999525$.
In 200 hours of work $P_c = 1-(1-0.7447)^2 = 0.935$.

However, we should bear in mind that the power supply to all the consumers upon the failure of the generator feeders is provided up the moment of complete exhaustion of the reserve capacity, and with the further failure of the feeders, it is necessary to disconnect the consumers accordingly.

Calculation of reliability of the distribution system power supply. Let us carry out a comparative calculation of the reliability of the power supply of the distribution systems with different diagrams of the supply line.

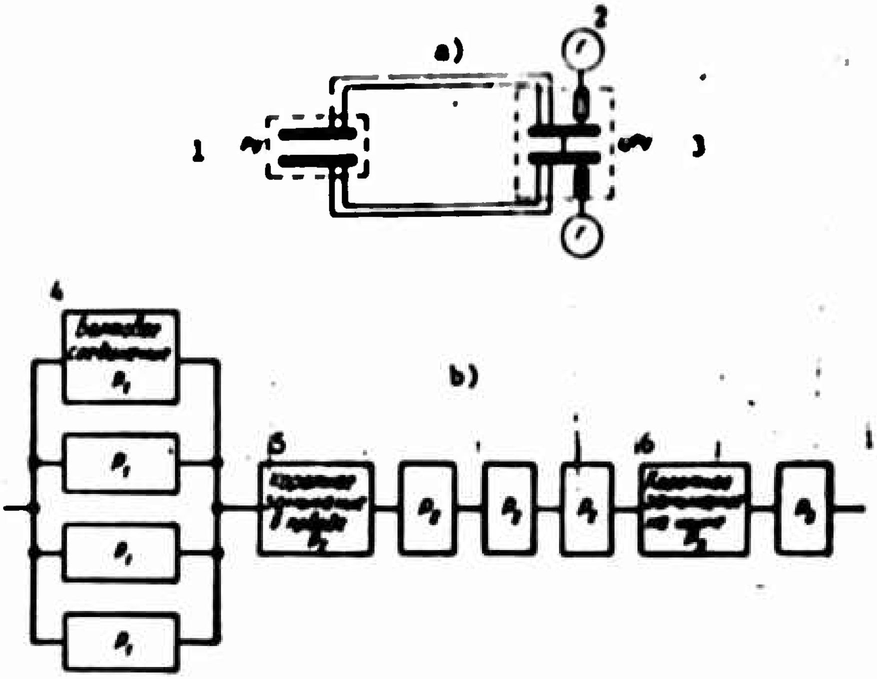

Fig. 2.9. Diagram of calculation of the reliability of the unprotected line of distributing system feed: a - structural diagram; b - calculated diagram.
Key: 1. Distribution system, 2. Generator, 3. Central distribution system, 4. Bolted connection, 5. Circuit in the wire, 6. Short-circuit in the busbar.

Unprotected lines for the distribution system's supply are given in fig. 2.9.

The system includes a bolted connection with $\lambda_1 = 0.0001 \cdot 10^{-3}$, short circuit in the wires with $\lambda_2 = 0.0001 \cdot 10^{-3}$, for 1 m, and short-circuit for the distribution busbar $\lambda_3 = 0.001 \cdot 10^{-3}$. The reliability of the elements included for 1000 hours of work is determined as

$$P_1 = e^{-t \cdot 2 \cdot 0.0001 \cdot 10^{-3}} = e^{-t \cdot 0.0002 \cdot 10^{-3}} = 0.9986;$$

$$P_2 = e^{-t \cdot 25 \cdot 0.0001 \cdot 10^{-3}} = e^{-t \cdot 0.0025 \cdot 10^{-3}} = 0.9962;$$

$$P_3 = e^{-t \cdot 0.001 \cdot 10^{-3}} = 0.9982.$$

The total reliability is

$$P = [1 - (1 - P_1)^4] P_2^4 \cdot P_3^2 = 0.9868.$$

Feed-lines with one-sided protection of the distribution system are given in fig. 2.10.

The system includes the same elements as in system of fig. 2.9, but in addition the cutout with $\lambda_2 = 0.01 \cdot 10^{-3}$.

The reliabilities of the elements included for 1000 hours of work is determined as follows:

$$P_1 = e^{-t \cdot 3 \cdot 0.0001 \cdot 10^{-3}} = e^{-t \cdot 0.0003 \cdot 10^{-3}};$$

$$P_2 = e^{-t \cdot 0.01 \cdot 10^{-3}};$$

$$P_{12} = P_1 \cdot P_2 = e^{-10^3 (0.0003+0.01) \cdot 10^{-3}} = e^{-0.0103} = 0.9890;$$

$$P_I = 1 - (1-P_{12})^2 = 1 - (1-0.989)^2 = 0.9999879;$$

$$P_3 = e^{-10^3 \cdot 0.0025 \cdot 10^{-3}} = e^{-0.0025} = 0.9962;$$

$$P_4 = e^{-10^3 \cdot 0.001 \cdot 10^{-3}} = e^{-0.001} = 0.9982;$$

$$P_{1d} = P_I \cdot P_3^2 \cdot P_4 = 0.999879 \cdot 0.9962^2 \cdot 0.9982 = 0.99.$$

The total reliability is

$$P = 1 - (1 - P_{1d})^2 = 1 - (1 - 0.99)^2 = 0.9999.$$

Feed-lines with two-sided protection are given in fig. 2.11. The reliabilities of the elements included in 1000 hours of appraision are determined:

$$P_{13} = P_1 \cdot P_2 \cdot P_3 = e^{-10^3 (4 \cdot 0.0001 + 2 \cdot 0.01 + 25 \cdot 0.0001) \cdot 10^{-3}} = e^{-0.0229} = 0.9772;$$

$$P_I = 1-(1-P_{13})^4 = 1-(1-0.9772)^4 = 0.999999973 \approx 1;$$

$$P_4 = e^{-10^3 \cdot 0.001 \cdot 10^{-3}} = e^{-0.001} = 0.9982;$$

$$P_{II} = 1 - (1-P_4)^2 = 1 - (1-0.9982)^2 = 0.99999675.$$

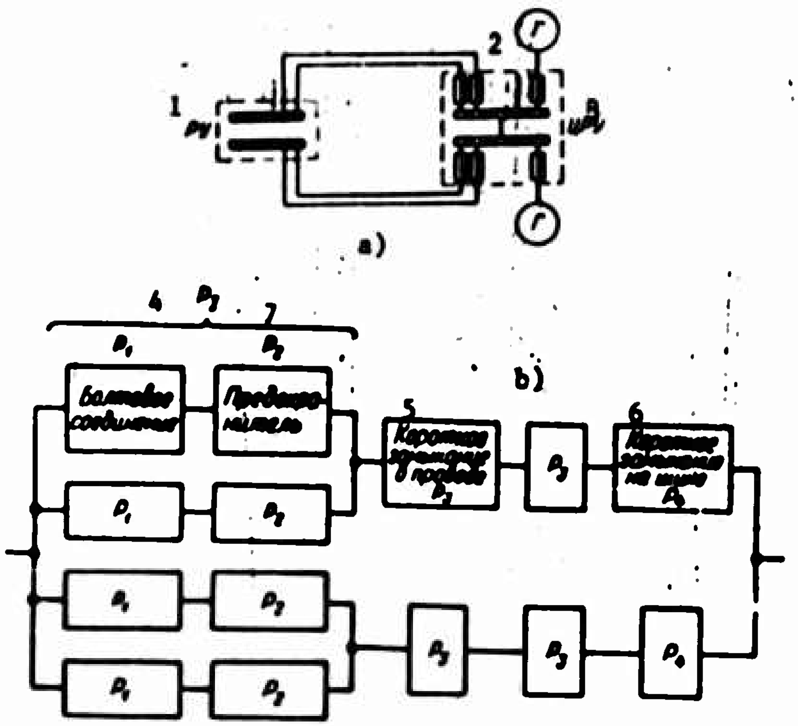

Fig. 2.10. Diagram of calculation of the feed-line reliability with one-sided protection: a - design diagram; b - calculation diagram.
Key: 1. Distribution system, 2. Generator, 3. Central distribution system, 4. Bolted connection, 5. Circuit in the wire, 6. Short-circuit in the busbar, 7. Cutout or fuse.

The overall reliability is

$$P = P_I \cdot P_{II} = 0.99999675.$$

From the calculation we can see that the most reliable feed-circuit of the distribution system is the angular four-channel system with two-sided protection for the feed-line.

Example 2*. Calculation of the Reliability of the A-C Power System.

Let us assume, that from statistics we know the intensity of failure of units included in the electrical power system:

- For elements of voltage regulation and frequency $\lambda = 2 \cdot 10^{-7}$ 1/per hour;
- for the protection unit elements $\lambda = 1 \cdot 10^{-7}$ 1/per hour;
- for the contact-lazy generator $\lambda = 2.9 \cdot 10^{-5}$ 1/per hour;
- for constant speed drive $\lambda = 45.2 \cdot 10^{-5}$ 1/per hour.

To determine the probability of the absence of a dangerous situation for a four-channel power system, for a 10 hour flight.

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* The failure of auxiliary elements, wires, and the reliability of electric power supply to secondary distributing devices is not examined in this example.

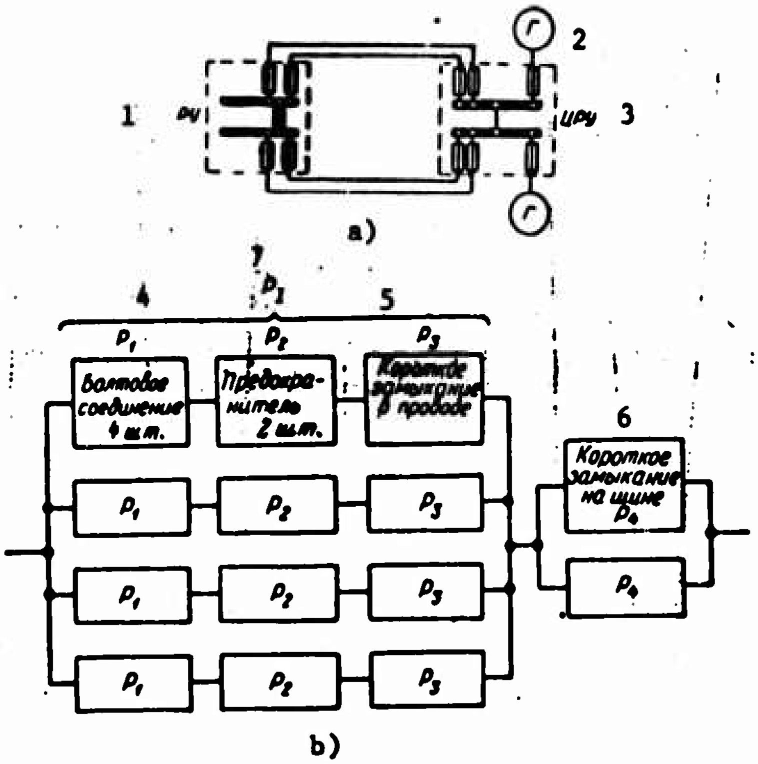

Fig. 2.11. Diagram of calculation reliability of the feed-line with two-sided protection: a - design system; b - calculation system.
Key: 1. Distribution system, 2. Generator, 3. Central distribution system, 4. Bolted connection, 4 pieces, 5. Circuit in the wire, 6. Short-circuit in the busbar, 7. Cutout or fuse, 2 pieces.

The probability of failure-free work of the unit for a 10 hour flight is determined according to the formula of the exponential law.

1. For a voltage regulator consisting of 53 elements,

$$P_{p.H} = e^{-2\cdot 10^{-7}\cdot 53\cdot 10} = 0.99989.$$

2. For frequency regulator consisting of 41 elements,

$$P_{p.ch} = e^{-2\cdot 10^{-7}\cdot 41\cdot 10} = 0.99993.$$

3. For the protection unit consisting of 245 elements,

$$P_{b.e.y} = e^{-1\cdot 10^{-7}\cdot 245\cdot 10} = 0.99976.$$

4. For the contactless generator,

$$P_r = e^{-2.9 \cdot 10^{-5} \cdot 1 \cdot 10} = 0.99972.$$

5. For the constant speed drive,

$$P_{pr} = e^{-45.2 \cdot 10^{-5} \cdot 1 \cdot 10} = 0.9955.$$

The probability of failure-free work of a single channel of the electric power system is determined as,

$$P_k = P_{pr} \cdot P_r \cdot P_{p.H} \cdot P_{p.ch} \cdot P_{b.e.y} = 0.9948.$$

The probability of failure-free work of a four-channel system without taking into consideration the determined combination of the double failure, will amount to

$$P_c = 1-(1-P_k)^4 = 1-(0.9948)^4 = 0.999999999269.$$

The probability of origination of failures of the system, caused by certain combinations of double failures of the regulation and voltage units, will be

$$Q_{oc} = Q_{p.H} \cdot Q_{b.e.y} = 48 \cdot 10^{-6} \cdot 50 \cdot 10^{-6} = 24 \cdot 10^{-10}.$$

The fear of double failures resulting in a dangerous situation,

$$\beta = \frac{Q_{o.c}}{1-P_k} = \frac{24 \cdot 10^{-10}}{1-0.9948} = 4.62 \cdot 10^{-7}.$$

The probability of a absence of a dangerous situation for a four-channel system will be determined by

$$P_c = (1 - \beta Q_K)^4 - (1 - \beta)^4 \cdot Q_K^4 = (1 - 4{,}62 \cdot 10^{-7} \cdot 5.2 \cdot 10^{-3})^4 -$$

$$- (1 - 4{,}62 \cdot 10^{-7})^4 \cdot 0.0052^4 = 0.999998977.$$

Section III. Aircraft Electric Power Supply Systems.

Chapter 1. Electric Power Transmission and Distribution Systems.

1. Principal Elements and Classification of Electric Power Supply Systems.

The electric power supply system is the connecting link between the sources of energy and consumers and consists of the following elements:

1. Electrical Conductors, intended for transmission of electric energy from the sources to the consumers.
2. Distribution systems (DS) intended for receiving energy from the sources and distributing it to the consumers.
3. Equipment for protection of the sources of energy, consumers, and wires, against short-circuits and overloads.
4. Switching equipment intended for control.
5. Control equipment of sources, consumers, and distributing systems.
6. Devices against interferences in the work of the radio-engineering and instrumental equipment.
7. Equipment for protection against static electricity.
8. Installation and assembly parts. The electrical power supply systems are classified according to a number of features:

According to their purpose their are divided into feed- and distribution systems. The simplified diagram of a system is given in fig. 1.1.

Feed-Systems transmit electric power from the sources to the feed points, primary and secondary distributing systems.

The Distributing Systems transmit the electric power from the feed points to the consumers.

With respect to the type of current in voltage the electric power supply systems are subdivided into 5 groups:

1. D-c low voltage systems (47, 27, and 12 v).
2. D-c high voltage systems (112 v and higher).
3. Three-phase a-c high voltage systems (200/115 v and higher).
4. Single-phase a-c high voltage systems (115; 200 v, and higher).
5. Three-phase and one-phase a-c low voltage systems (47, 36, 27, and 12 v).

Direct-current, low voltage and three-phase alternating-current, high voltage power supply systems being the most widely used in most power systems. In a secondary power system three- and one-phase a-c lines as well as low voltage d-c lines are usually employed. Direct-current, high voltage lines are seldom used today.

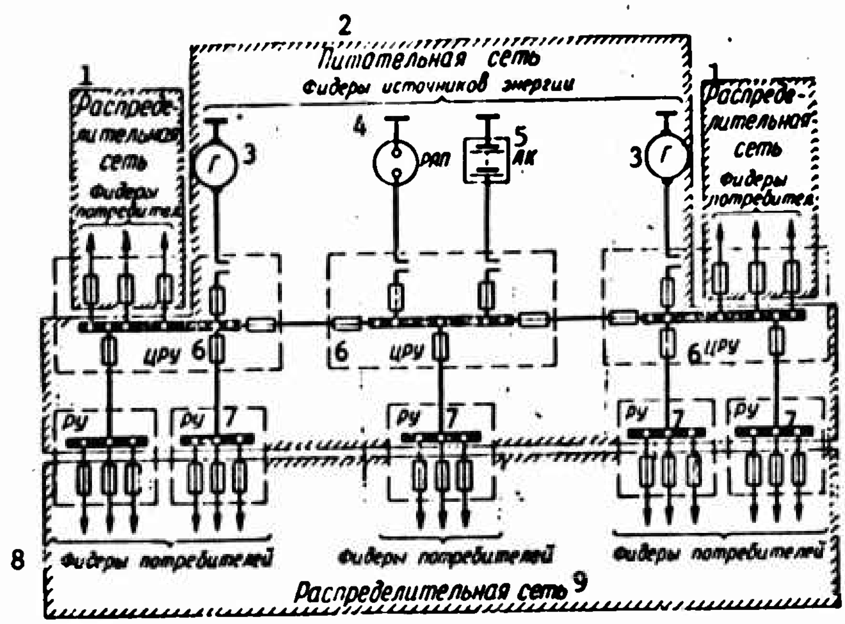

Fig. 1.1. Circuit diagram of the feed and distribution systems. Key: 1. Distribution system, consumers-feeders; 2. Feed system, energy source feeders; 3. Generator; 4. Automatic starting relay; 5. Automatic control; 6. Central distribution system; 7. Distribution system; 8. Consumers-feeders; 9. Distribution system.

With respect to the electric power transmission system, designs are:

1. Single wire,
2. Two-wire,
3. Three-wire,
4. Four-wire.

With respect to electric power distribution they are:

1. Centralized,
2. Mixed,
3. Decentralized,
4. Separate.

With respect to configuration they are:

1. Disconnected (radial and main-line),
2. Closed (radial, main-line, rectangular, and angular).
3. Combined.

With respect to protection they are:
1. Protected,
2. Non-protected.
With respect to their channels they are:
1. Single channeled,
2. Multi-channeled.

The name of the electrical power system is usually based on configuration, channels, protection, and purpose, or as the explaining elements, the type of current, voltage, transmission system, and distribution system.

For example: Angular, multi-channel protected feed-line of a direct current with a voltage of 27 v.

2. Principal Technical Demands to the Electrical Supply System.

The general technical demands examined for electric power supply systems are applied to electric power lines. Let us not assume specific features of those demands and ways of meeting them.

1. The electrical power supply system under normal and emergency conditions of operation of the aircraft should provide high reliability of electric power transmission from sources to consumers.

2. When individual energy sources fail, and wires are broken off or short-circuited, the supply system should retain its working capacity and transmit energy of satisfactory quality.

3. The electrical power supply system should have a minimum flight weight and assure high quality of electric power transmission from the sources to the consumers.

Let us examine the principal ways of meeting the above mentioned demands.

High Reliability, Fail Proof Work, and Vitality of the Electric Power Supply System may be reached by:

- forming of several rings of the supply system, i. e., creating a main electric power supply ring with primary, central distribution systems, and the secondary electric power supply ring with secondary distribution systems;
- making multi-channel feed-lines in the main and secondary energy rings;
- making two-sided protection for the electric power supply lines in the main and secondary energy rings;
- selectivity of operation of the protective devices during short-circuits in the feed-lines, i.e., automatic disconnection of the damaged

line and attention of the working capacity of the remaining supply system;

- selective operation of the protection during short-circuit in the distributing wires of the central distribution system and its distributing system, i. e., automatic disconnection of the damaged busbars and retention of the working capacity of the remaining supply system;
- stringing supply lines of the energy supply rings on two sides of the aircraft;
- multilateral feed of the main energy ring. The number of power supply points should correspond to the number of energy sources;
- automatic switching over of important consumers from the distribution busbar which has been taken out of commission, to the one operating normally;
- automatic switching over of important consumers to the emergency supply line when the principal feed-line has been taken out of commission;
- assuring a minimum dispersion of voltages on the distribution busbars;
- automatic and selective disconnection of the consumer from the distributing busbar during short-circuiting of its feeder and overloads;
- installation of the supply line of the shortest route with a minimum of connections and transmission resistances in the conducts;
- an effective reduction of the flight-weight of the electrical supply system may be reached by: using a-c with a voltage of 200/115 v, instead of d-c 27 v;
- a single conductor power transmission system instead of a two-conductor one;
- using aluminum wires instead of copper wires;
- improving the quality of insulation;
- connecting high capacity consumers to the distributing devices lying near the energy sources;
- correct selection of wires from conditions of heating and permissible voltage loss.

The quality of electrical energy depends on the selection of the energy sources, the transmission and distribution system, the configuration and protection of the power supply lines. The principal measures to be taken for increasing the quality of electric power supply are:

- parallel work of all the energy sources for the main supply system;
- multi-channel and angular configuration of the feed supply systems;
- feeding the high capacity consumers from the distributing devices lying near the energy sources;
- connecting the working windings of the voltage regulators to the central distributing system busbars;

- installation of the network over the shortest routes with a minimum amount of connections and transition resistances at the conducts;
- selectivity and rapid operation of the protective devices.

In order to combat parasitic magnetic and electrical fields, some wires and individual assemblies are shielded, electrical filters and dischargers are installed, individual elements of the aircraft's body are interconnected with metal, etc.

3. Direct-Current Electric Power Transmission Systems.

On aircrafts with d-c electric power systems two systems for transmitting electric power have been widely adopted, namely the one-conductor and two-conductor systems.

In the One-Conductor Transmission System (fig. 1.2) only the plus wire is brought up to each source and consumer. The metal body of the aircraft is used as the minus-conductor. In this case we have to bear in mind, that over the aircraft's body considerable current flows (thousands of A), therefore individual elements of its structure should have a reliable conduct.

Advantages: 1. The body has a high conductivity and we may count voltage losses only in the plus-conductor.

2. The weight of wires and power line devices in comparison with the two conductor systems, is reduced by up to 40%, while the dimensions of the power line devices are reduced to 15 - 20%.

3. The assembly and operation of the power line is simplified considerably.

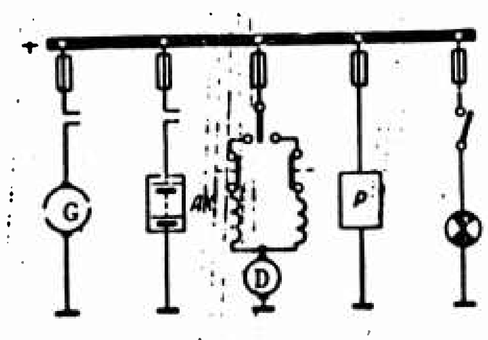

Fig. 1.2. Diagram of a single conductor direct-current electric transmission system.

Short-comings: 1. Connection of any wire with the body is short-circuiting of the electrical system, and therefore the demands to the electrical insulation are increased.

2. If an extraneous plus becomes connected into the consumer's circuit, the latter operates arbitrarily.

The single-wire supply system has become widely used in all types of aircraft.

In the two-conductor electric power transmission system (fig. 1.3) direct and inverse wires are connected to bus the source into the consumers.

A protection and control equipment, as a rule, is installed on the plus circuits. The protection equipment in the minus circuits is provided only for units having an inverse conductor, connected with the mass.

Advantages: 1. When any wire is short-circuited on to the body the system retains its normal working capacity and goes out of commission only on simultaneous short-circuiting of two conductors on the body.

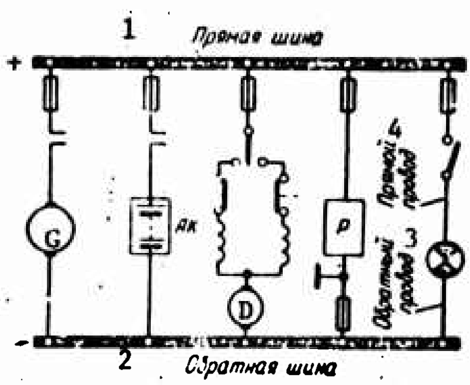

Fig. 1.3. Diagram of the two-conductor d-c electric power transmission system. Key: 1. Direct busbar; 2. reverse busbar; 3. reverse conductor; 4. direct conductor.

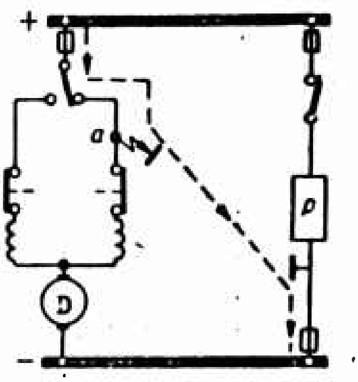

Fig. 1.4. Failure of a radial feeder upon short-circuiting of the power electric mechanism wire in a two-conductor system.

2. Small hazard for the service personnel, because in such a network, touching even a bare wire is not dangerous.

However, these two advantages are correct only for the two-wire systems in which the consumers (mainly radio-equipment), having a connection between the inverse conductor and the mass are absent.

3. Small interference level, because in principle the direct and inverse conductors represent a bifilar conductor.

Short-comings: 1. With identical voltage loss values in the two-wire system the wire cross-section is twice and the weight is four-times greater than in the single-conductor system.

2. The presence in the two-conductor transmission system of consumers with diverse conductors grounded to the mass may result in additional emergency conditions (fig. 1.4 and 1.5).

When a power mechanism is turned on the short-circuiting of its plus conductor to the mass (short-circuiting in point a, see fig. 1.4) causes the flow of the short-circuit current to the minus conductor of the radio-equipment, which is grounded into the mass. The mass of the current is shown with the broken line. Since the conductors and the cutout of the electric power mechanism are calculated for a large current, then the wires of the mentioned radio-equipment are calculated for small currents, the short-circuiting first of all will result in ignition of insulation or burning out of the wires in the minus circuit of the radio-equipment. This makes it necessary to install cutouts in the minus wires of the conductors which are grounded.

When the fuse burns out in the minus grounded circuit of the radio equipment with a simultaneous short-circuiting of the plus wire of the electric mechanism to the mass (short-circuiting in point b), the capacity of which is commensurable with the capacity of the radio-equipment, there will be a false operation of the electric mechanism, as it is shown in fig. 1.5.

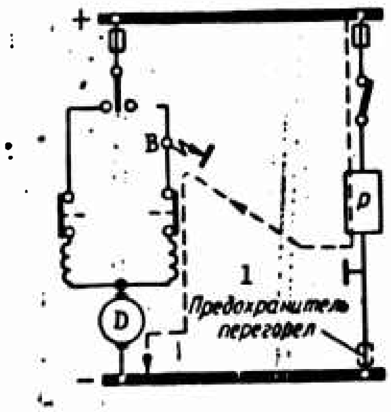

Fig. 1.5. False operation of the electric mechanism upon short-circuiting of its conductor in a two-conductor system. Key: 1. The fuse has burned out.

The two-conductor electric power transmission system had been exceptionally popular at the early stage of development of electrical equipment of aircraft, when the length of the electric power supply lines was not great, and the body of the aircraft was wooden or of a mixed construction.

In individual cases the two-conductor system is used with a common minus, into which the consumer's two-wires are also brought up: one from the plus busbar, and other from the combined minus wire. In the combined minus conductors, the currents of all the consumers connected to them never flow simultaneously, and therefore, the cross-section of the combined conductor may be used smaller than some of the cross-sections of all the separate minus conductors of the consumers. The two-conductor supply systems with a combined reverse conductor is the logical conversion from the conventional two-conductor system to the single-conductor system.

In modern aircraft the two-conductor transmission system is used only in individual sectors of the power lines, where it is impossible to assure reliable contact between the minus wires and the aircraft's body. This pertains mainly to the electrical units located on the engine. The minus wire in this case is brought up to the fire-proof partition.

With a single conductor system of electric power transmission the especially important consumers may be controlled over a two-conductor system, which practically excludes the possibility of false operation.

In pilotless aircraft, in order to increase the vitality and reliability of electrical systems it is also advisable to use two-conductor electric power transmission systems.

4. Alternating-Current Electric Power Transmission Systems.

On aircraft with a-c electric power systems, the electric power transmission systems, and especially their operations, are determined by the number of phases and are represented by the single-phase and three-phase transmission systems.

Single-Phase Alternating-Current Transmission Systems.

A single-phase alternating-current is transmitted by two-systems: the one-conductor and the two-conductor system, which possess the advantages and short-comings noted in paragraph 3.

Three-Phase Alternating-Current Transmission Systems.

The three-phase a-c electrical energy depending on the type of generator and the specific features of operation of the aircraft, may be transmitted by the following systems: the two-conductor, with grounding of one-phase; the three-conductor, with grounding of the power neutral; and the four-conductor systems.

The two-condcutor transmission system is possible if the source of electric energy is a three-phase generator without a power zero let out. In this case the body of the aircraft is used as the third conductor (fig. 1.6).

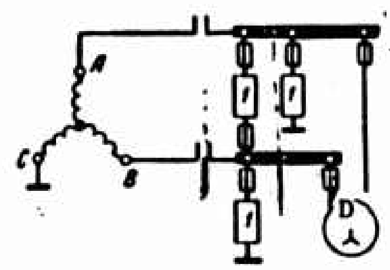

Fig. 1.6. The diagram of the two-conductor system of three-phase a-c transmission with grounding of one phase.

Advantages: Reduction of the weight of transmission lines to the use of the body of the aircraft as the third conductor.

Short-comings: 1. Because of the low resistance of the aircraft's body there is asymmetry of linear voltages in the consumers, which increases with the increase of distance of the consumer from the energy source.

2. With the same linear voltage in the two-wire system, the voltage between the body and the linear conductor is $\sqrt{3}$ times greater than in the grounding by the zero-conductor, which increases the dangers of shock.

3. When one of the line conductors is broken, a part of the single phase consumers becomes connected in series, which results in abnormal conditions of their work, while the three-phase consumers receive single phase feed.

The Three-Conductor Transmission System is used in systems were the source of electric energy is a three-phase a-c generator with insulated neutral lines (fig. 1.7).

Three-phase consumers are supplied over a three-conductor system, the single-phase consumers use the two-conductor system.

Advantages: 1. With symmetrically distributed single-phase loads the asymmetry of line voltages with practically absent.

2. The probability of appearance of short-circuits through the body of the aircraft is decreased.

3. The insulation of the neutral prevents leaks of current harmonics which are multiples of three.

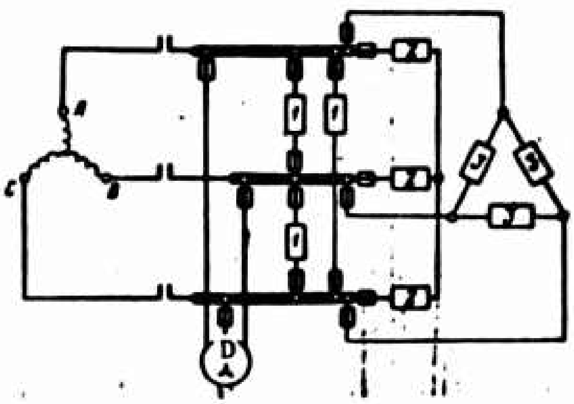

Fig. 1.7. Diagram of the three conductor three-phase a-c transmission system with insulated power neutral.

Short-comings: 1. When one of the wires is connected to the mass (a hidden short-circuit):

a) the danger of contact with wires of the other phases increases;

b) the potential diagrams change in the electronic equipment, supplied with power from the section with the closed phase, which may cause disruption of the work of the equipment;

c) an over-voltage forms on the filters' condensers;

d) it is required to raise the rated amplitude voltage of the equipment's insulation to 585 v.

2. A potential danger of short-circuiting through the body is created.

3. Rapid warnings and discovery of short-circuits to the mass is not provided for consumers which are turned on only in flight.

4. To feed single-phase consumers with a voltage of 115 v, it is required to install a large number of small transformers.

5. To connect single-phase consumers, a two-fold switching equipment is required, because with connections through single-fold equipment, wrong starting is possible.

6. When there is an inequality of resistances of single-phase consumers, connected in a star-pattern, the rise of phase voltage at individual ones among them is possible.

The Three-Conductor Transmission System with a Grounded Power Neutral is possible, if the electric power source is a three-phase synchronous generator with a power zero let-out. The body of the aircraft is used as the zero conductor (fig. 1.8).

Three-phase consumers are supplied over the three-condcutor circuit, and for consumers which have a let-out zero, the body of the aircraft is used as a false conductor.

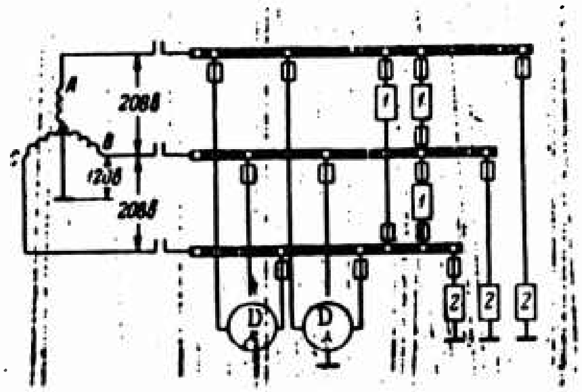

Fig. 1.8. Diagram with a three-conductor system of a three-phase alternating current transmission with a grounded power neutral.

Advantages: 1. With three-phase loads and symmetrical distribution of single-phase loads over the phases the line voltage asymmetry is practically absent.

2. The presence of two working voltages U_f and $U_1 = \sqrt{3}\ U_f$ assures the possibility of connecting single-phase consumers on the line and phase voltage of the generators without transformers.

3. Reliability increases and the weight of the wires decreases somewhat in connection with the four conductor system.

4. The work of the automatic protective devices of the generators is simplified.

5. The vitality of the electric system is increased, since three-phase electric motors upon damage to one or two conductors may operate for a short time as two-phase and as a single-phase motors.

Short-comings: 1. Poor shape of the phase voltage curve, caused by the third harmonic in voltage. In modern generators the short-coming is practically eliminated.

2. Closing of any line wire to the mass causes short-circuiting.

The three-phase system with a grounded power neutral has a number of advantages over the other systems of transmission and distribution and is recommended for use in aircraft as the principal system.

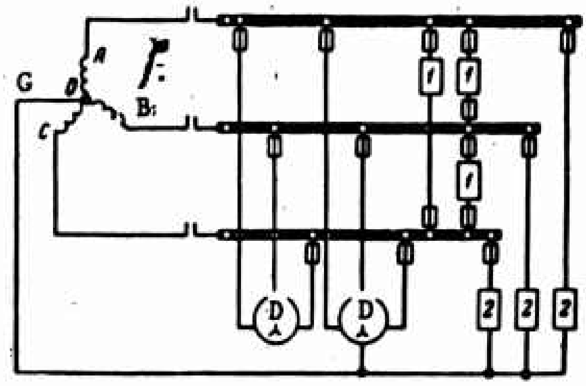

Fig. 1.9. Diagram of a four-conductor system for a three-phase a-c transmission.

The four-conductor transmission system is possible if the source of electrical energy is a three-phase synchronous generator with a let-out power zero (fig. 1.9).

Advantages: The system possesses the merits marked in paragraphs 1 and 2, 4 and 5, of the three-conductor system with the grounded power neutral, and in paragraph 2, for the three-conductor system.

Short-comings: The system possesses the short-comings marked in paragraphs 1, 2, and 3, and 5 for the three-conductor systems.

5. Electric Power Distribution Systems.

Depending on the purpose and dimensions of the aircraft four electric power distribution systems are used: centralized, mixed, decentralized, and separated.

The principles of the systems' work differ, consequently, the quality of electric power supply and the methods of calculations are different.

The above mentioned systems extend in an equal degree to the systems of electric power supply with direct and alternating current. The first three systems provide for a parallel connection of the energy sources, and attained wide popularity in the initial electric power supply systems.

On an aircraft we can use all the four distribution systems simultaneously.

The Centralized Electric Power Distribution System (fig. 1.10), is characterized by the fact that the energy from the feed sources is delivered to a single central distributing system (CDS) and then from the CDS-busbars it is distributed between the individual consumers.

The protection of energy sources and consumers' feeders, control and regulation of energy sources, are concentrated in the CDS, which is located in the immediate proximity from the crew. The consumer control equipment, as a rule, is located on the corresponding functional boards and panels.

Advantages: 1. When individual energy sources go out of commission, the consumers continue to receive normal feed from the power reserves of the generators.

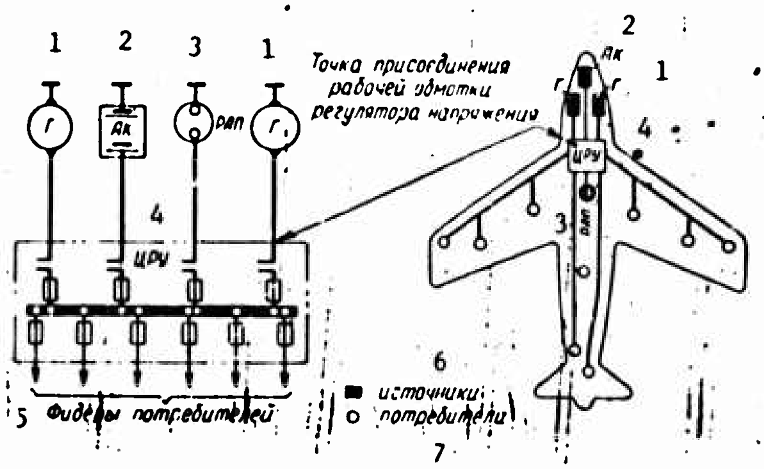

Fig. 1.10 Centralized system of electric power distribution.
Key: 1. Generator; 2. storage batteries; 3. automatic starting relay; 4. central distributing system; 5. consumers' feeders; 6. sources; 7. consumers.

2. The voltage at the CDS-busbar is maintained constant within the limits of accuracy of the voltage regulator work, their working windings are connected directly to the CDS-busbars.

3. The feeders of all the consumers have a potential, equal to the potential of the CDS-busbars, and consequently, the voltage at the consumers' terminals is determined only by the change in the current consumed by the given unit.

4. With the corresponding selection of the feeder wire cross-section for various consumers, at the unit terminals, we can obtain any required voltage, optimum for the given unit.

5. Convenience in operation, checking, and finding faults in the electrical system.

Short-comings: 1. Low vitality of the electric power system, since upon short-circuiting at the CDS-busbar all the consumers lose their feed.

2. Unwieldy CDS, because in it, the protective equipment for all the energy sources and consumers' feeders is concentrated as well as the control and regulation equipment for the electric power sources.

3. The great weight of the electrical system due to considerable length of the feeders of the energy sources and consumers.

The centralized electric general distribution system became used most extensively in light aircraft. Upon the increase of the number of sources and consumers the centralized distribution system becomes unwieldy and heavy. However, it can be successfully used in secondary electric power supply systems, providing a differentiated high quality electric power supply to the consumers.

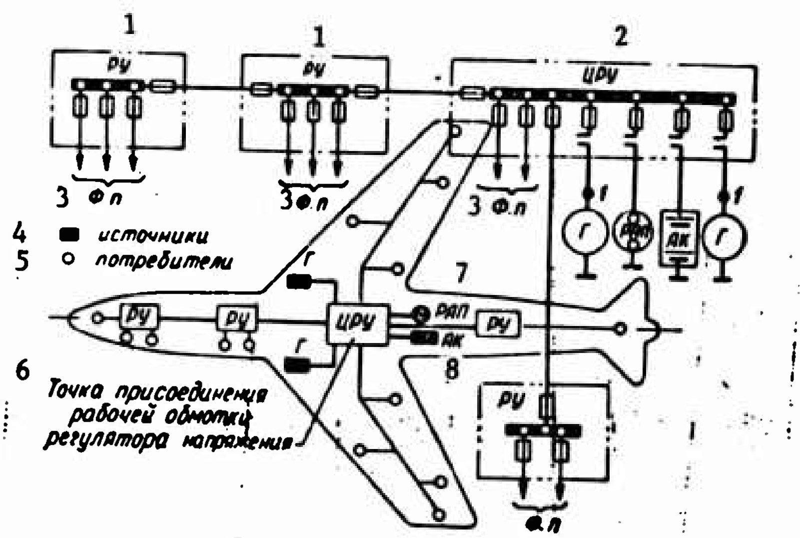

Fig. 1.11. Mixed electric power distribution system.
Key: 1. Distributing system; 2. central distributing system; 3. consumers' feeders; 4. sources; 5. consumers; 6. point of connection of the working-winding of the voltage regulator; 7. automatic starting relay; 8. storage batteries.

With a Mixed Electric Energy Distribution System all the energy from the feed sources is delivered to a central distributing system (CDS), then from the CDS-busbar a part of the energy is distributed directly to the power consumers, and another part is delivered to the grouped distributing systems (DS) from which the other consumers receive their feed.

In fig. 1.11 we portray the simplified diagram of the mixed electric power distribution system. In order to reduce the weight of the conductors it is advisable to place the CDS at the shortest distance from the energy sources and power consumers, and place the group distribution systems at spots, where the consumers and the control panels in the crew's cabins are concentrated.

The protection of the energy source feeders and certain consumers is concentrated in the CDS, the protective devices of the feeders of the other consumers are concentrated at the corresponding DS. The regulation and control of the energy sources is performed from the DS which is in the crew's cabins.

Advantages: 1. The mixed system possesses merits, marked in paragraphs 1, 2, 3, and 4, for the centralized system, paragraphs 3 and 4 pertaining only to consumers receiving power supply from the CDS-busbars.

2. The vitality of the feed system is increased in comparison with the centralized distribution system, because with the correct selection of the system's configuration and its protection, short-circuits in the feeder or on the DS busbar deprive of current only the given DS, retaining the integrity of the remaining part of the power system.

3. The design of the distributing devices is simplified, because of the decentralization of the protective and switching equipment.

4. In connection with the approach of the CDS to the sources and their power consumers, and of the DS to the consumers, the weight of the electric lines decreases, its installation and operation is simplified.

Short-comings: 1. Insufficient vitality of the power system, since upon a short-circuit at the CDS-busbar all the consumers lose their feed.

2. Loss of an invariable voltage of the energy sources(on the CDS busbar),the voltage at the DS-busbars does not remain constant but changes in relation to the number and capacity of consumers, which are connected simultaneously to the given DS, which uses the quality of the electric power supply, in comparison with the consumers receiving feed from the CDS.

3. The voltage at all the DS differs. It has a large fluctuation range in comparison with the voltage at the CDS, therefore, in working out the basic electric power systems for the consumers, we cannot permit connection of the busbars through the consumers' circuits.

The mixed system of electric power distribution is used in medium aircraft, having a small number and capacity of energy sources, a limited number of high power consumers, a moderate quantity of low power consumers, and a sufficiently branching electrical line system.

In order to increase the reliability we resort to sectioning of the DS-busbars and use multi-channel feed conductors with selective protection.

With a decentralized electric power distribution system (fig. 1.12), the feed sources deliver energy accordingly to the nearest CDS. From the CDS the energy is delivered to the nearest consumers, and DS located in the crew's cabins, which supply feed mainly to non-power consumers and to the DS, installed in the places of group location of consumers.

In order to increase the reliability of the electric power system all the CDS are connected between one another as a result of which the feed system is closed in many places.

Advantages: 1. The decentralized distribution system possesses all the merits marked for the mixed system.

2. The presence of several CDS increases substantially the reliability of power supply when the feed lines are broken, or during several types of short-circuits on the busbars.

3. The reliability of feed for the DS-busbars increases, because it is possible to divide them into sections and to supply with power from a different CDS.

4. It is possible to use a ring-shaped power line with selective protection, which raises the reliability of the electric power supply.

Short-comings: 1. The decentralized distribution system possesses the short-comings noted in paragraphs 2 and 3 for the mixed system.

The decentralized electric power supply system has beocme widely used in all kinds and types of aircraft, especially in medium and heavy aircraft.

The divided elctric power distribution system (autonomous) is characterized by the fact that each source serves only its own group of consumers.

The divided system is used in cases when the parallel work of electric energy sources is impossible because of their unequal electrical parameters, for example, the different tolerances with respect to voltage or frequency with the same rated values.

The divided electric energy distribution system includes elements of centralized or mixed systems.

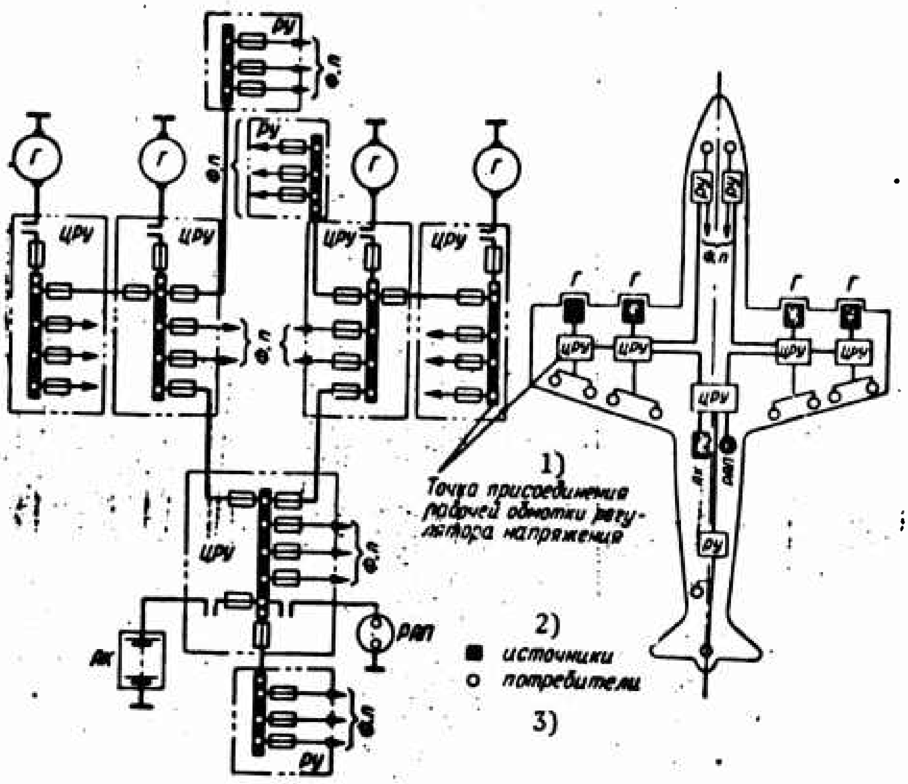

Fig. 1.12. The decentralized electric power distribution system.
Key: 1. Point of connection of the operating coil of the voltage regulator; 2. sources; 3. consumers.

The absence of parallel work of energy sources does not permit a rational utilization of the available power, impedes the starting of powerful consumers, and increases the fluctuations in the voltage in the network when they are turned on.

When the energy source goes out of commission, the entire group of consumers lose their power supply.

The divided distribution system is used in the primary and secondary power supply systems. It is entirely unavoidable in a-c power supply systems with unstable frequency, and possible as the operational variation in systems with alternating current of a stabilized frequency when the generators go out of synchronism, and also for independent work of generators during take-off and landing in order to increase the reliability of power supply to duplicated consumers. Moreover, the divided distribution system is used extensively in secondary power systems, the energy sources of which are electric machine or static transformers of direct current into alternating with a stabilized frequency or alternating current into direct current.

6. Power Supply System Lay-Out.

The lay-out (a geometry) of the power supply lines is the principal factor in assuring reliability and uninterrupted work in the supply of power to the consumers, determines the quality of the electric power supply, the selectivity in operation of the protective devices, and the vitality and weight of the system. The lay-out is the basis for naming the power supply system.

With respect to the lay-out the power supply systems are divided into three types: the open, closed, and combined. Each type of the power supply system may have different ways of transmission and distribution of electric energy, different numbers of channels, and different protective devices for the feed lines.

Let us examine the merits and short-comings of the principal types of lay-outs applicable to d-c power supply systems, since all the principal premises apply entirely to the a-c power supply systems.

Open Power Supply Systems.

In the open power supply systems the electrical energy is delivered to the distributing busbars in only one direction. They may be represented by the two principal types: radial and main line.

Radial Feed Lines. In fig. 1.13 a, we show a normal radial single-channel feed line.

Advantages: 1. It is easy to calculate and to select the protective equipment, which operate selectively during short-circuits and overloads.

2. It is simple to install and operate.

3. It has a minimum wire weight, since the DS may be placed at a location where the consumers are concentrated.

Short-comings: 1. The voltage on the busbar of the secondary DS changes in relation to the number and capacity of the consumers, connected simultaneously to the given DS.

2. When there is a short-circuit at the CDS busbar the entire electric power system goes out of commission.

3. When the DS supply line is broken or short-circuited, the consumers connected to this busbar are deprived of electric energy.

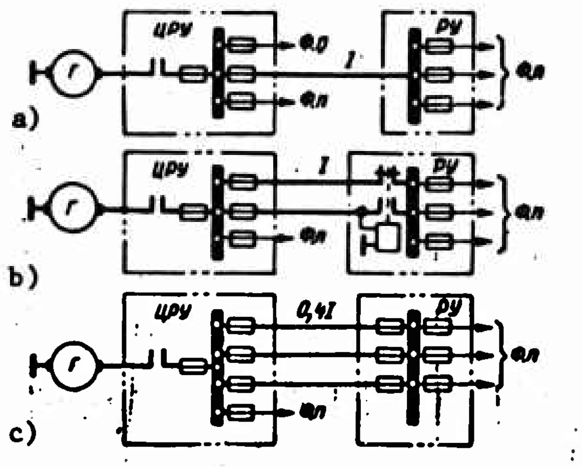

Fig. 1.13. Disconnected radial supply systems.

The disconnected radial single-channel supply system has become widely used, however, due to the low reliability and vitality is not recommended for future aircrafts.

In fig. 1.13 b, we present the divided radial single-channel supply system with automatic feed lines reservation.

Advantages: 1. The system possesses the merits marked for the divided radial single-channel supply system.

2. When the principal feed line is broken or there is a metal short circuit, the reserve line is automatically switched on, providing uninterrupted supply to the consumers.

Short-comings: 1. The system possesses the short-comings, marked in paragraphs 1, 2, and 3 (in particular short-circuits on the busbar) for the divided radial single-channel supply system.

2. With alternating short-circuits at the main line, the contactor is not switched over, since the voltage in the line in this case remains relatively high (19 - 23 v).

3. During a short-circuit in the distributing wire of the DS the contact goes into the "bell"-operating condition.

4. The weight of the conductor doubles in comparison with the single-channel system.

In fig. 1.13 c, we present the disconnected radial multi-channel supply system.

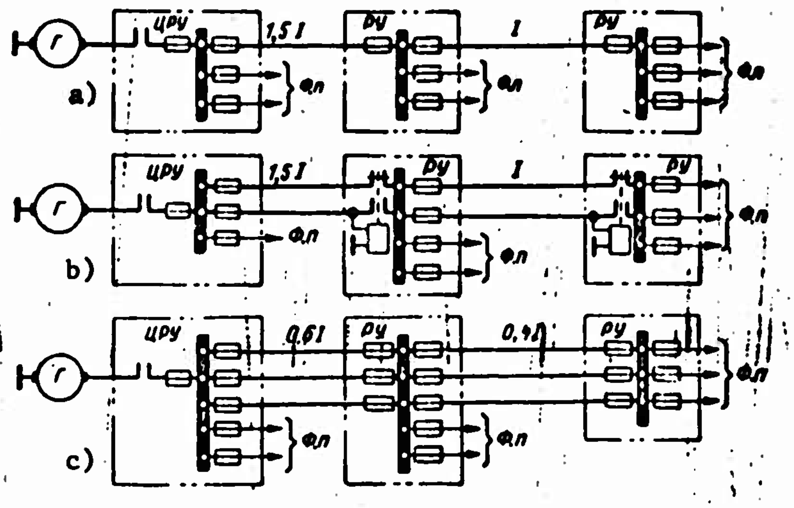

Fig. 1.14. Divided main-line feed systems.

Advantages: 1. The network possesses merits noted for the open radial single-channel supply system.

2. The use of independent supply systems numbering not less than three, and having a bilaterial protection, increases substantially the reliability of DS power supply during short-circuits or breaks of conductors without increasing the weight of the conductors in comparison with the single-channel network.

The system possesses the short-coming, marked in paragraph 1 for the open radial single-channel feed system.

Main-line Feed Systems. In the open main-line feed systems the distribution of busbars are connected in series, and the electric energy is delivered to them from one side only. The typical systems are presented in fig. 1.14.

The systems possess the advantages noted for the corresponding systems of the open radial supply system.

Short-comings: 1. The systems have the same short-comings as the similar radial ones.

2. The voltage at the busbars of the secondary and supplementary distributing systems (DS) changes in relation to the number and capacity of consumers, which are connected simultaneously to these dis-

tributing devices, the fluctuations in the voltage increasing with each busbar connected in series.

3. Upon a break or short-circuit of the intermediate lines, there is in all the next distributing busbars deprivation of current.

4. With a large number of adjacent sectors it is difficult to provide for the selectivity of operation of protective devices by means of fuses or thermal protective automatic devices, since for selectivity it is necessary to have a stepwise increase of the time lag of the protective devices, from the end of the line to its start, when the short-circuit currents flow through them. For reliability of operation of protective devices it is necessary, that the rated currents of the protective equipment of the adjacent sectors would differ by not less than one and one-half times. With a greater number of adjacent sectors protection becomes too coarse and its reliable action in the main sectors is not assured. This situation is intensified in a high power electric power system, because of the peculiar external characteristics of the generators, where the short-circuit current in the system decreases upon the approach of the short-circuiting point to the beginning of the line.

Closed Power Supply Systems.

Closed power supply systems are such in which the distribution device busbars receive feed from several independent energy sources from different sites, at least from two sites.

By the independent energy source we understand such sources in which the working conditions disrupted or resulted in damage to one of them (for example short circuit at the busbars of one CDS) does not cause the others to go out of commission.

The closed power supply systems may be divided into four principal types: radial, main-line, grill-work, and ring-shaped.

Merits: 1. With the symmetrical distribution of loads of the busbars under normal operating conditions of the network, the decentralizing current in the middle link is absent. Symmetrical DS busbars, in this case will be under identical voltage and the corresponding sectors of the system between the CDS and DS may be calculated for a fully permissible voltage loss.

2. The systems possess the merits, noted in the corresponding divisions for the divided radial feed systems.

3. The systems in comparison with the divided systems have a high reliability and vitality when there are breaks and short-circuits in the feed lines and DS-busbars.

4. When there is a short-circuit at the CDS-busbar, only part of the power system goes out of commission, ceasing the power supply to the corresponding consumers.

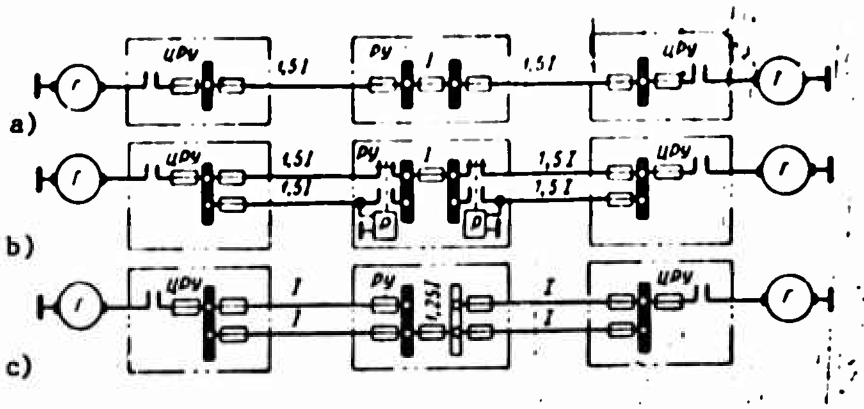

Fig. 1.15. Closed radial supply systems.

Radial Supply Systems (fig. 1.15) possess the merits marked in paragraphs 1 through 4. Special interest is represented by the closed radial two-channel supply system shown in fig. 1.15, c*.

The network retains the normal power supply for the DS-busbars when there is a short-circuit in any supply line, which is assured by the selctive operation of the protective devices.

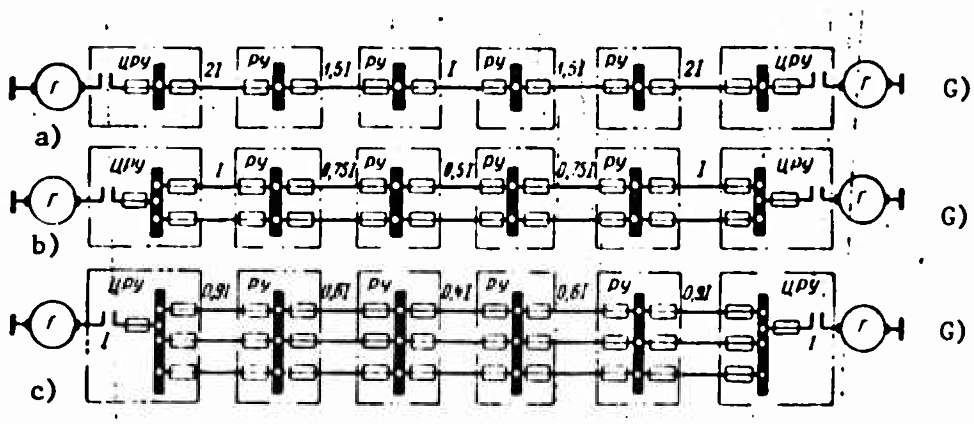

Fig. 1.16. Closed main-line supply systems.

Main-line Power Supply Systems (fig. 1.16) possess the merits marked in paragraphs 1 through 4, however in these systems it is difficult to assure a selective operation of the protective devices when there are short-circuits in the line or the distributing busbars, while the series connection of the DS-busbars decreases their reli-

* Proposed by the author.

ability in comparison with the radial ones. The use of multi-channel independent supply lines numbering no less than three, with bilateral protection, increases somewhat the reliability of DS-power supply without increasing the conductor weight in comparison with the single-channel system.

Ring-Type Supply Systems represent multiple closed networks with the presence of several parallel connected electric power supply sources (fig. 1.17).

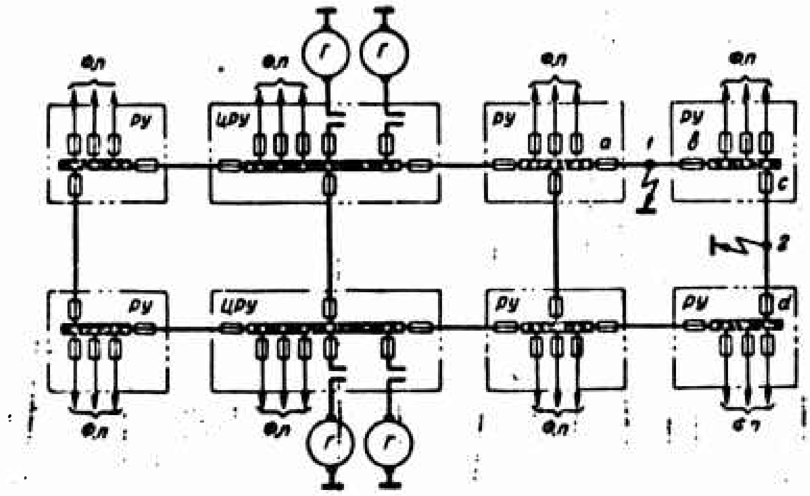

Fig. 1.17. Ring-shaped power supply system.

Such systems possess a high vitality and provide uninterrupted power supply to the consumers, when individual feed-lines are broken, in as much as the busbars of the distributing devices receive feed from several directions.

However, with such a complex lay-out of the feed systems, it is practically impossible to select correct protection.

Let us examine this with a concrete example (fig. 1.17). Let us assume that there is a short-circuit in the section a) and b) only the protective devices a) and b) should operate, and this may occur when these apparatuses have the minimum time of operation with respect to all the other protective devices of the network, including equipment c) and d). But only in these cases will the devices a) and b) operate and disconnect the damaged sector a) and b) before all the other protective devices of the network will operate, and the entire remaining system will continue normal work. If however, there is a short-circuit at sector cd, then obviously, in order to disconnect this sector under the condition that the entire remaining network would continue normally, we should have the minimum time for operation of devices c)and d) and this is contrary to the selection of the protective equipment proceeding from the conditions of the preceding emergency conditions at the ab sector.

Because of the above, the protection of such feed systems is ineffective and results only in a reduction of their reliability.

Such systems are used without protective equipment, but they represent considerable fire-hazards during short-circuits.

Ring-Type Supply Systems. In ring-type supply systems the energy is delivered to the distribution busbars from a minimum of two sites from independent energy sources, and each line of the system has protective devices on two sides. The standard ring-type diagrams of supply systems with selective protection*, as shown in fig. 1.18, has all the merits of the systems for other lay-outs and have a number of advantages over them. .

In fig. 1.18, a, we show a ring-type three-channel supply system in which the energy is delivered over three-channels to the primary distributing busbars, and over two channels to the secondary.

Merits: 1. When any one source of energy goes out of commission or any wire is torn, all the consumers receive normal feed.

2. The DS-busbars possess a high reliability of electric power supply through sectioning and supply from various CDS.

3. The system makes it possible to place the distributing systems near the concentration of the consumers.

4. The initial distribution busbars have a stable voltage, dependent only on the accuracy of the work of voltage regulators.

5. With a symmetrical distribution of loads on the the bushbars, the colliding current between the CDS and in the middle link of the DS is absent.

6. When there is a short-circuit in any wire the bilateral protective device operates, isolating the one wire from the system.

7. When there is a short-circuit on the CDS busbar, only one-half of the distributing busbars is deprived of current, whereas when there is a short-circuit on the DS busbar only that busbar which has the short-circuit is deprived of the current.

Short-comings: 1. Great difficulties in selecting the protection, which would provide for a selective and rapid operation when there is a short-circuit.

2. Insufficiently rapid action of the protective devices when there is a short-circuit on the CDS busbars.

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*Proposed by the author in 1950.

In fig. 1.18, b, we show the ring-shaped five-channel feed system, which has a main and a secondary power ring. The number of the latter is determined by the number of concentrated groups of consumers. The energy to the primary distributing busbars is delivered over five channels and to the secondary busbars over three channels.

The principal condition for a confident selective operation of the protective devices when there is a short-circuit in the feed lines of the distributing busbars is the presence of not less than three channels with a bilateral protection of each. The increase of the number of channels improves the selectivity and raises the speed of the protection's action.

The selectivity of operation of protective devices during a short-circuit in the wires or distributing busbars of the secondary energy ring is provided for by the corresponding selection of the rated values of the protection taking into account the following relationship:

$$I_1 = I_2 = I_3 = I_4 = I < I_5,$$

$$I_1 + I_3 = I_2 + I_4 = 2I > I_5,$$

where $I_1 \div I_4$ - are the rated protection currents. Practically, I_5 is selected equal to $1.2 \div 1.5I$.

Merits: 1. The system possesses the merits noted in paragraphs 1 through 5 for the ring-shaped three-channel feed system.

2. The selectively operated protection d vices are easily calculated and chosen.

3. When there is a short-circuit in any line of the feed system the bilateral protective device operates through the air-rise of the current in it, in comparison with the others.

4. When there is a short-circuit in any busbar of the DS or CDS the corresponding protective device operates and the busbar is isolated from the system. When there is a short-circuit at the DS-busbars the first to operate is the I_5 protective device, and then the rest are applicable to it.

5. In comparison with system a) (through the increase of number of channels and decrease of the rated value of the protective system) a selectivity and rapidity of action of its operation during short-circuits increases.

The short-coming of the system is the relatively slow action during short-circuits at the CDS busbars, however, upon the increase of the

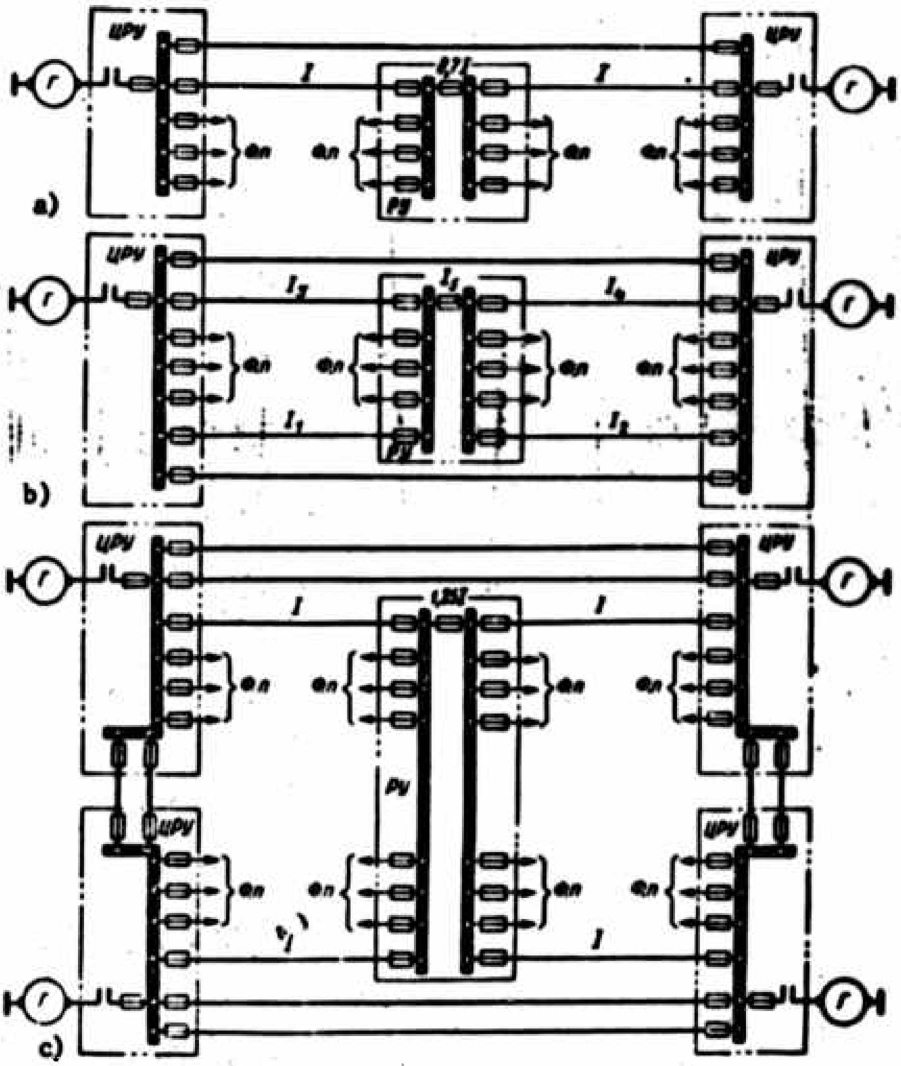

Fig. 1.18. Ring-Shaped Feed Systems:
a - three-channel; b - five-channel;
c - six-channel.

number of sources the speed of the action increases.

In fig. 1.18, c, we give the ring-shaped six-channel feed system having a main (two-channel) and secondary energy rings.

The energy is delivered to the primary distributing busbars over six channels, and over three channels to the secondary.

The system attains all the merits marked for the ring-shaped five-channel feed system, and moreover, has a more rapid action and wider selectivity of operation of the protective devices for short-circuits in the main-ring lines and at the CDS-busbars. This is attained in the first case through the increase in the number of channels of the main-ring and the reduction of the rated value of the protection, and in the second case due to a three-fold increase of the current in the lines, which reach the damaged busbars in comparison with the others.

In this way the multi-channel ring-shaped feed systems with selective protection practically retain their vitality up to the last source of energy with multiple short-circuits and breaks of the feed-line. They (especially diagram c) possess an absolute reliability and vitality in comparison with the other lay-outs of feed systems and assure uninterrupted energy supplied to consumers. These systems should be the basis in the development of all types of power supply systems.

Combined Feed Systems.

The combined feed systems consist of all types of combinations of various types of closed and open feed systems.

The distributing devices, including elements of the closed feed-system, receive power supply from several independent energy sources on several sides, and the distributing systems, including elements of open feed systems, receive feed from a single direction. The number of different combinations of such feed systems is very large and it does not appear possible to examine all of them. Let us examine the first of the typical systems of the combined supply system, as presented in fig. 1.19, from which we can see the principal merits and short-comings of such feed systems.

In these systems the busbars of the primary distributing systems (CDS) are interconnected by two-channel feed lines with a bilateral selective protection and for the primary (main) two-channel energy ring, which possesses high reliability of power supply during multiple short-circuits in the feed lines or on the busbars of the distributing

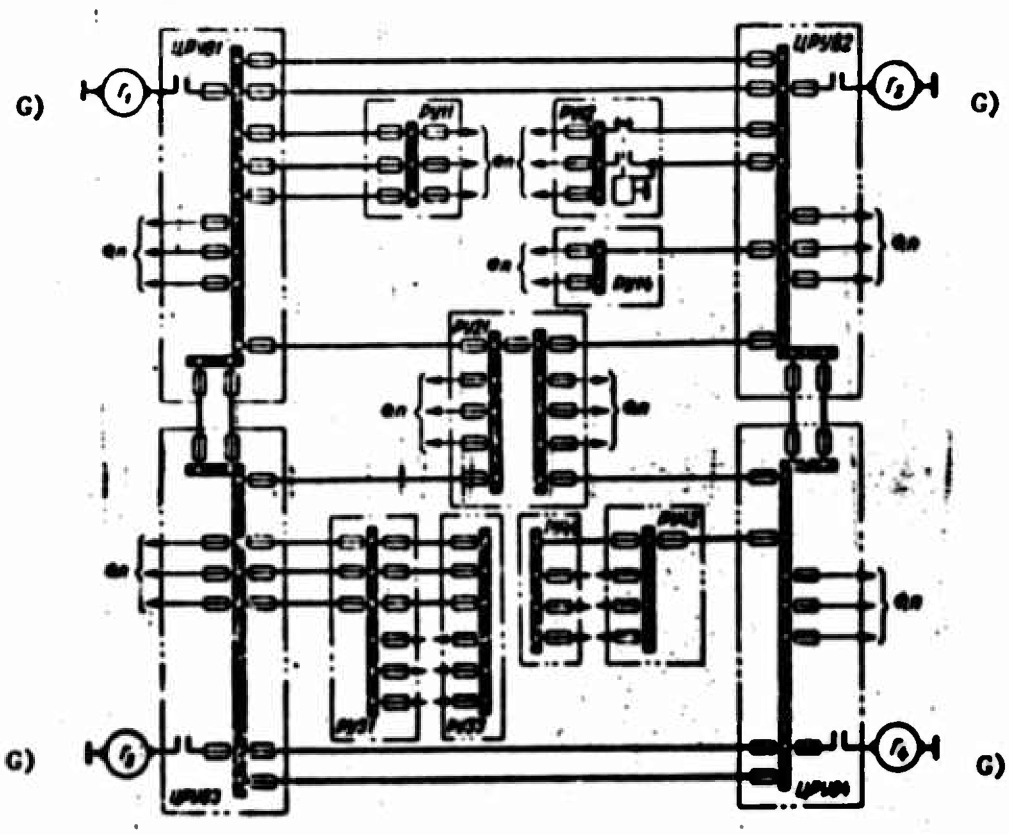

Fig. 1.19. The Combined Feed System.

devices, and also when individual sources of energy go out of commission.

The wires of the secondary distributing system DS21 are supplied with feed according to the system of the secondary three-channel ring and possess, as noted above, high reliability.

The busbar of the secondary distributing system DS14 is fed according to the system of the open one-channel radial system.

The busbar of DS12 is fed according to the system of the open radial single-channel feed system, with a reservation of the feed line.

The busbar of the DS11 is fed according to the system of the open radial three-channel feed system.

The busbars of the secondary distributing system DS42 and DS44 are fed according to the system of the open main-line single-channel feed system.

The busbars of DS31 and DS33 are fed according to the system of the open main-line three-channel feed system.

As we can see from the examination of the typical system of combined feed system, its individual units possess the properties of the corresponding feed systems, which have been examined in greater detail earlier.

The character of all manner of combinations forming various types, is determined by the purpose of the aircraft and the role of one distributing system to another, in providing the reliability of power supply for the consumer and the flight-safety proceeding therefrom.

The elements of the closed ring-feeder system with selective protection, have a dominating significance and determine the principal merits of the combined feed systems.

The elements of the open feed-systems for secondary consumers should be introduced with a limit, and only with a definite predominance with respect to weight and selectivity of operation of their protective devices.

Chapter 2. Protection of the Electrical Systems of Aircraft.

1. The Purpose, The Principal Requirements, and Classification of Protection of the Power Systems.

When aircrafts are in operation, damage is possible to the power system, power sources, consumers, and equipment, causing short-circuit and overloads of the equipments' elements.

In modern aircrafts the short-circuit currents reach several thousands of amperes, and when they last for a sufficient length of time they may cause ignition of insulation, welding of the current-carrying elements with the body of the aircraft, destruction of individual structural units and equipment. This may result in putting-out of commission individual types of electrical equipment.

The overload of individual elements of electrical equipment results in the same consequences as those caused by short-circuits.

The protection of the electrical system on an aircraft is intended for preventing serious consequences, which may result in short-circuits and overloads, and therefore should possess reliability, selectivity, rapid action, simplicity, and minimum dimensions and weight.

Reliability of operation of protective devices depends on their sensitivity, which is determined by the ratio of the current with a metallic short-circuit in the protective zone, and the current for operating the protective device. The greater the sensitivity of the proctective device, the more reliable is its operation under emergency conditions. The protection should not result in false disconnection of the protected sector, i. e., should not react to causes which do not produce emergency conditions in the system, and at the same time should operate reliably under emergency conditions. The faults in the protection equipment itself should not result in false disconnection of a system operating in good order.

Selectivity of the action of the protective system provides for disconnection of only the damaged sector, retaining the vitality of the rest of the power system. In order to assure selectivity of the action, the sequence in operation of the protective devices, connected into the system in series, should be such, that first the apparatus would operate, which is located in the immediate proximity of the loaction of the short-circuit, and then (in closed fields) the next protective elements would operate which possess a time-lack according to the ascending line from the consumer to the source.

The above mentioned sequence of operation of the protective devices of the system is attained by the corresponding selection of their second characteristics.

The time-lag of the protective system excludes the possibility of its operation during the action of brief starting currents, which may exceed appreciably the rated currents in the protected sector of the system.

The rapid-action of the protective system decreases the effect of short-circuits on the work of the consumers, retains the quality of the electric energy, reduces the size of damage, occurring during brief short-circuits, retains the stability of the work and the vitality of the power supply system.

In order to decrease the effect of the damaged sectors on those in good order, the protective system should react instantaneously, especially during short-circuits in the generator feeders and in the main sectors of the feed system.

The simplicity, minimum dimensions and weight of the protective equipment make it possible to arrange it in the most rational places, raise its working reliability and also simplify its operation.

The problem of simultaneous satisfaction of all the above mentioned properties is the most difficult one in planning the power system lines.

Protection of feed systems, generators and their feeders from short-circuits according to the principle of their action is divided into three main-groups: 1. current protection reacting to the value of the current in the circuit-protect, operates when the current in the circuit-protect exceeds established values and operates without delay (current cut-off) or with a time delay (maximum current protection).

2. The differential current protection, based on the principle of comparison of currents at the beginning and end of the protected sector of the system (longitudinal protection) or in two parallel lines with identical parameters (lateral protection). The protection of this group operates without time-lags practically instantaneously as soon as the difference between the compared currents exceeds the previously established value.

The differential-current protection of d-c feed systems, in spite of rapid action, has not become practically useful because of a series of short-comings: complication of design, increase of weight, appearance of additional wires and conducts, presence of dead zones, necessity of an outside source of energy (in the longitudinal protection systems), and additional maximum-current protection [10].

3. The minimum of voltage protection, operating with a time-lag upon the degrees of the voltage in the terminals of the generators up to a certain prescribed value.

2. Maximum-Current Protection of D-C Systems.

The maximum-current protection apparatuses include fuses and bimetallic automatic devices of all types. To these and the time-lag free cut-outs of the SB and BV type, high-melting fuses of TB type time-lag fuses of the IB type, and bi-metal automatic devices of the AZS and AZR type are used.

The most important parameter of the maximum-current protection is the value of the critical current to which the given type of protective device can be subjected to an infinitely long time under specific external conditions. Thus, for example, under normal atmospheric conditions and surrounding temperature of + 20°C, the fuses have the following approximate values of critical currents:

$$SB - I_{cr} = (1.2 - 1.4)\ I_{rated}$$
$$BV - I_{cr} = (1.2 - 1.25)\ I_{rated}$$
$$TB - I_{cr} = (1.4 - 1.57)\ I_{rated}$$
$$IB - I_{cr} = (1.25 - 1.75)\ I_{rated}\ .$$

The effectiveness of the action of the maximum-current protection equipment is determined most precisely by their second characteristic, which represent the interdependence of the operating time of the equipment on the value of current flowing through it.

The number of the second characteristics enable us to determine the necessary speed of action in turning-off short-circuit currents, the required sensitivity to overload currents, and the required time lag during starting currents and brief load-changes.

Fuses of the type BV and SB have a dependent number-second characteristics, i. e., the time of their burning out depends on the value of the current flowing through them. The greatest difference in number-second characteristics of various fuses is observed in the small current region. Thus, with the same current, the operating time is always greater in the fuse with a greater rated current value. This property is used for assuring selective work under small short-circuit currents or overloads. With large currents the number-second characteristics of fuses merge and the selectivity of their operation is not assured.

The fuses of the BV type have little time lag, the SB type fuses possess greater time lag. However, both types fail to provide protection to consumers with large starting currents.

Fuses are simple, have small dimensions, and possess sufficient rapidity of action. Their principal short-coming is the absence of actual selectivity during large currents and individual control of the state.

In order to assure selective operation of fuses, their characteristics should be identical, while the transient resistances between the fuse-link and holder are minimal and stable. The fuses should have a luminous or mechanical signal system, indicating that they are burned out.

High-melting fuses of the TB type have a small time-lag, are used for protection of power circuits with small starting currents.

Time-lag fuses of the IB type possess considerable time-delay, which is attained by the special design.

In fig. 2.1 we give the ampere-second characteristic of the time-lag fuse. Sector 1 responds to the relatively small currents, characterizes the inertial part of the fuse, and determines in principle the time constant for heating the massive copper-plate. Sector 2 corresponds to greater currents, during which the brass fuse-links burn out. Because of this, the inertial fuses are installed in the circuits of consumers with large starting currents.

Among the short-comings of the fuses are: dependence of operating time on the surrounding temperature and state of the contacts, their single time effection, which prevents the checking of their characteristics in the process of operation, the variations in ampere-second characteristics of the result of ageing of the material, and the difficulty of visual evaluation of the fuse operation.

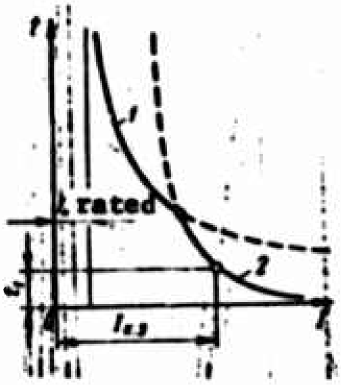

Fig. 2.1. Ampere-Second Characteristics of a Time-Lag Fuse. I_{rated} - consumer's current; I_{sc} - short-circuit current; t_1 - operating time of the fuse.

Bi-metallic automatic protection devices with respect to their kinetic diagram are divided into two types: AZS and AZR. The principle of operation of the automatic devices is based on the sag of the bi-metallic elements during heating. The bi-metallic element consists of two metal-plates welded together, which have different temperature linear expansion coefficients.

The AZS type automatic protective devices do not have a free disconnection of the control parts and the contact system, the automatic devices are turned on manually or automatically, permit forceful attention of the protected circuit in the switched-on state independently of the value of current passing through the automatic device. The forceful attention is sometimes used for assuring operation of important consumers; armaments, communications, chassis, etc. The AZS are installed in the circuits which are outside of fire-hazardous sectors and may be used as switches.

The protective automatic devices of the AZR type with a free disconnection of the control units and contact systems are also automatic devices which are turned on manually or automatically and are switched off manuallv. The distinction from the AZS automatic device after operation, the AZR automatic device cannot be turned on manually and the circuit cannot be closed until the bi-metallic plate cools. The AZR in comparison with AZS has a better ampere second characteristics and greater disconnection power. In the AZR the circuit is broken in two points which assures better arc-distinguishing conditions.

In fig. 2.2 we show an ampere-second characteristics of the cooled (curve 1) and preliminary heated with current (curve 2) protective automatic device. Curves 1 and 2 have the same asymptotes. The operating time of the automatic protective devices just as that of the fuses, depends on the surrounding temperature.

The principal advantages of the automatic devices in comparison with the fuses are:

The presence of regulating elements, making it possible to obtain the required steepness of the ampere-second characteristics;

the possibility of rating the ampere-second characteristic before installing the automatic device on the aircraft in the process of operation;

simplicity of switching on and off of the circuit;

possibility of visual observation of the state of the automatic device in the process of operation;

the considerably greater thermal inertia (excluding the IB type fuses).

The maximum-current devices are used for protection of all the consumers and the power supply system feeders. In this case because of the large multiplicities of the short-circuit currents with respect to the rated value, the protective device assures a sufficiently rapid action and selectivity.

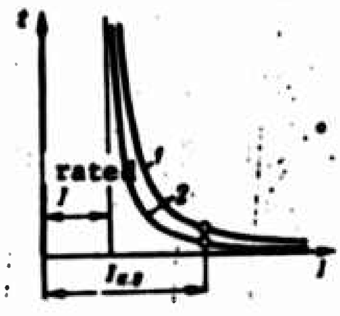

Fig. 2.2. Ampere-Second Characteristics of the Protective Automatic Device:cooled (1) and preliminary heated through (2).

The maximum-current protective devices are selected in such a way as to use to the maximum thermal possibilities of the objects protected, i.e., that should break the circuit only when the temperature of the object's elements reaches a maximum permissible value. In the ideal case, the ampere-second characteristics of the protection device should coincide with the thermal characteristic of the object protected. In this position of characteristics, the protective device is selected according to the rated current of the object protected.

However, in actual practice the characteristics coincide not in the entire range, because of which the protection of the consumers' circuits from a short-circuit and overloads is selected according to the rated current of the consumers, taking into account the character of their work.

$$I_{protection} = K \cdot I_{rated},$$

where $I_{protection}$ - is the rated protection current;

$K > I$ - is the reserve coefficient;

I_{rated} - is the rated current of the consumer.

If the consumer's current, under all conditions of its work, does not exceed the rated current, the protective device is selected for the next greatest current in comparison with the rated current. In this case the reserve coefficient approaches a unity, and for protection we can use visible, high-melting, and inertia protective devices, or bi-metallic automatic devices.

If the consumers under certain operating conditions use current which exceeds the nominal current, the protection is selected taking these conditions into account.

For d-c electric motors the starting currents reach the three- to eight-fold value of the rated. However, taking into account the brief character of the starting currents, the inertia-free protection should be selected under conditions of $I_{protection} > 0.7\ I_{starting}$. The inertia-free fuses, naturally, do not protect electric motors from overloads.

The most rational protection for such consumers are inertia fuses and bi-metallic automatic devices. In this case protection should be selected in such a way that its ampere-second characteristics would be lower than the ampere-second characteristics of the consumers or would approach them.

The maximum-current equipment protects mainly the power supply system and only partially protects the consumers from overloads. In as much as for the consumers, it is not the value of the current, but the heating of the insulation that is important; it is most advisable to protect them first of all by means of equipment built into the most heated part thereof.

During brief short-circuits in individual parts of the supply system, the protective device should disconnect the damaged sector, retaining the vitality of the power system.

The protection of the feed system should not react to brief short-circuits in the distribution system. This is reached by using a selectively active protection, the rated current of which for apparatuses connected in series is increased along the ascending line, from the consumers to the energy sources. However, the use of a selectively active protection results in certain delay in the process of disconnection of a short-circuit in the head-sector of the feed system.

In actual practice the protective equipment of a supply system is selected according to the total current of simultaneously operating consumers and consequently a current for its operation is considerably higher than the current for the operation of the protection of any of the consumers, which protects automatically the selectivity of the system's protection.

Under large third circuit currents, the operating time of the protective device becomes very small, and all the ampere-second characteristics will converge into the axis of the abscissa. Because of this, false operation of the protective devices is possible, the probability of which increases through the non-stability of the characteristics of the protective devices, especially of fuses. Moreover, the protection of the feeder system does not react precisely to intermittent short-circuits.

The selection of the rational system, geometry, and parameters of the maximum-current protection of the feed system in almost all the cases makes it possible to obtain the required selectivity, rapid action, and minimum disconnection time of the short-circuited sector from the part of the power supply system which operates in good order.

The maximum-current protection thanks to the simplicity, sufficient rapid action, and reliability, is today the principal type of protection for the power supply systems in aircraft.

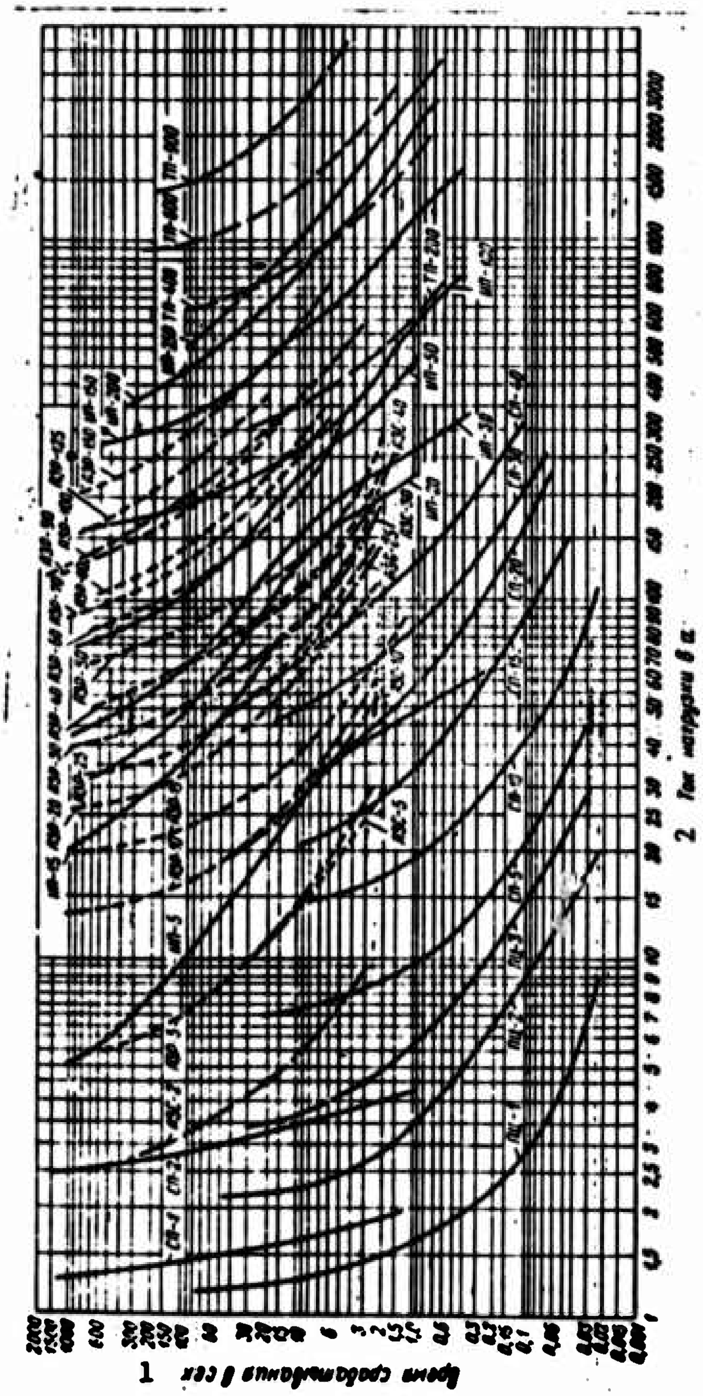

Fig. 2.3. Graph of the Ampere-Second Characteristics of the Maximum-Current Protection of the Power Supply System.
Key: 1. Operating time in seconds; 2. Load-current in amperes.

In fig. 2.3, we give the ampere-second characteristics of various apparatuses of the maximum-current protection of the power supply system, according to which we determine its rated current and the rapidity of action in relation to the value of the current flowing through it.

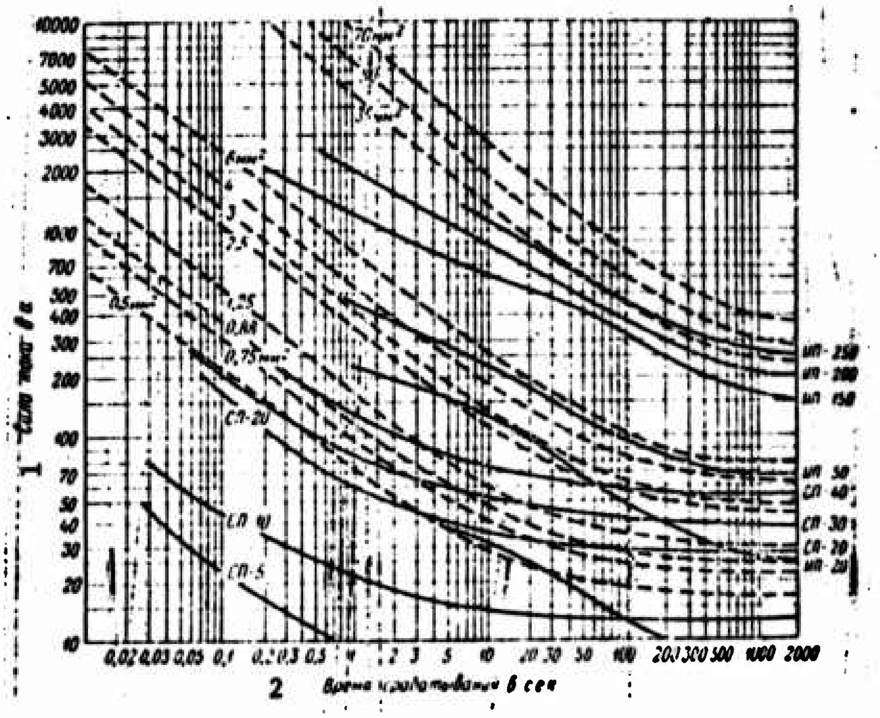

Fig. 2.4. Curve of the Coordination of the Ampere-Second Characteristics of the Wires and the Maximum-Current Protection.
Key: 1. Current power in amperes; 2. Operation time in seconds.

In fig. 2.4 we show the curve of coordination of the ampere-second characteristics of the conductors and the maximum-current protection, which makes it possible to determine the cross-sections of the conductors in relation to the protective equipments selected. For this purpose we used a graph given in fig. 2.5.

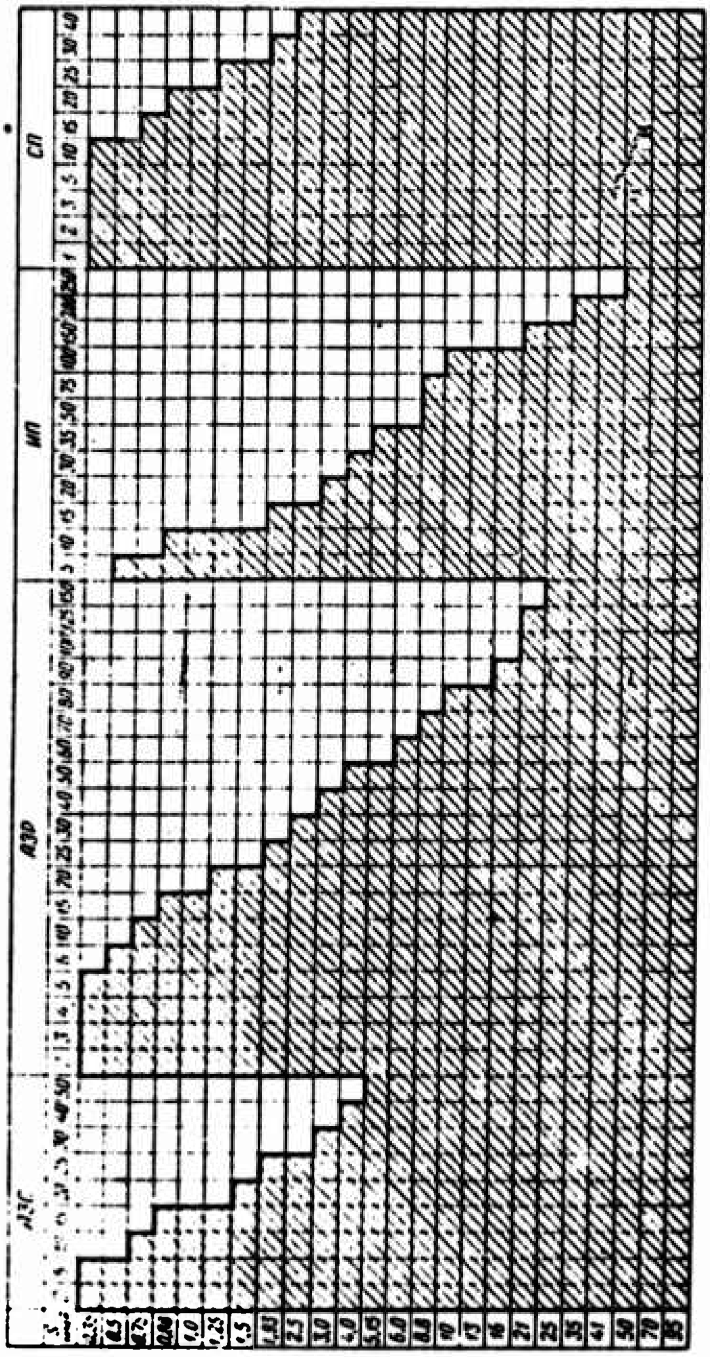

Fig. 2.5. Graph of Coordination of Protection and Wires of the BPVL with t_{ocrit} = from − 60 to + 50°C.

3. The Maximum-Current Protection of Alternating-Current Systems.

In the aircraft power supply system with an alternating-current for the protection of single-phase and three-phase feed and distribution systems we may use fuses and bi-metallic automatic cut-offs, used for the protection of the direct-current systems. However, the single circuit protection in three-phase systems should be used only for multi-channel sectors of the feeder-lines from the CDS, DS, and the three-phase consumers, in which the emergency situation does not arise upon operation of the protective device in a single phase.

For a-c single-phase protective automatic devices with a voltage of 27, 115, and 200 v, and three-phase with 200 v, are provided; the latter break open all three phases when one phase is overloaded. Multiplications of three-phase automatic protective devices have been developed which react to both the current overloads and the phase in breaks. Such automatic devices are necessary for protecting three-phase motors, starting of which, with a broken phase results in overheating. These automatic protective devices are equipped with remote control from the a-c system or from the operative d-c system.

The use of automatic devices for protecting d-c power supply systems is limited by the breaking capacity of their contacts. However, taking into account the considerable reduction of short-circuit current-value and improvement of switching conditions in the a-c circuits in comparison with d-c circuits, we should expect an extensive application of protective automatic devices in a-c systems. Nevertheless, it is necessary to improve further the designs of the protective automatic devices, in order to simplify them, increase the stability of the parameters, decrease the transient resistances, and increase the breaking capacity of the contacts.

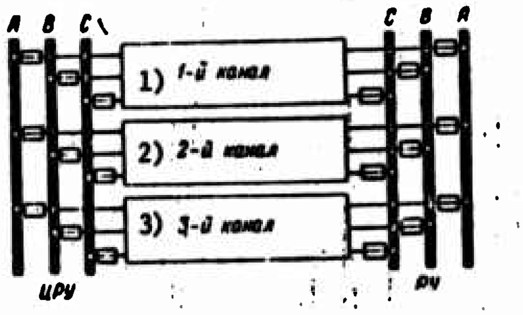

Fig. 2.6. Diagram of Protection of the Three-Phase A-C Power Supply System.
Key: 1, 2, 3, channel.

The maximum-current protection system has no auxiliary working elements (relays and conductors), auxiliary wires, etc. The maximum-current protection is simple, of small size and convenient calibration, possesses the necessary speed of action and high reliability.

In fig. 2.6 we give a diagram of the protection of the three-phase a-c supply system by fuses, or bi-metallic automatic devices (conventional and with current cut-off). Each phase is laid into three parallel lines, having a bilateral protective system. The three lines provide selective operation of the bilateral protective system during short-circuits between phases and of individual phases on the body (if the neutral is grounded),after which the line with the short-circuit is isolated from the system.

The splitting of each phase into three channels and combination of three phases in each cable, reduces noises in radio equipment from the a-c system and when one cable is damaged the symmetry is retained in all three phases.

In the three-channel feed system with a bilateral protection of each channel we can use fuses, single-phase and three-phase automatic devices.

4. Differential Protection of A-C Power Supply Systems.

The longitudinal differential protection of an a-c system with circulating currents in a single line portrayal is presented in fig. 2.7. At the beginning and at the end of the protected circuit, current transformers TT are installed, the secondary windings of which are accumulatively connected. The current transformers are intended for isolating the secondary windings from the primary current system and decreasing the current in the protective device circuits.

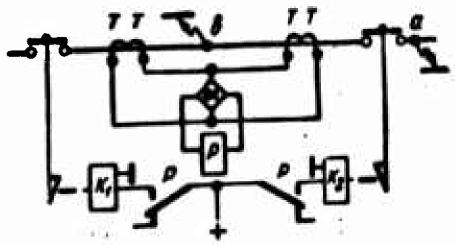

Fig. 2.7. Longitudinal Differential A-C Protection with a Circulating Current.

In the auxiliary wires, which connect the secondary windings of the current transformers, currents circulate which are equal to the secondary currents of the current transformers. Under normal working conditions and during a short circuit outside the protected sector (point a) the secondary currents add up. In this case in the winding of relay P, which is connected in parallel to the secondary windings of the transformers, the current is close to zero. During a short-circuit in the protective zone (point b) the phase of the current in one of the current transformers changes by 180° (during bilateral feed) or one of the initial currents becomes equal to zero (with a unilateral feed). In this case in the relay winding P, a current appears, the relay operates, and removes the conductors K_1 and K_2 from the cages. The damaged sector of the system is switched off. A break or short-circuit in the auxiliary wire may result in a false operation of the protective devices. For this reason this protective system did not become practically used in aircraft.

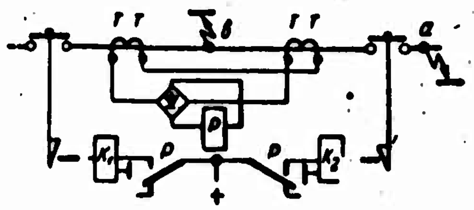

Fig. 2.8 Longitudinal Differential Protection of A-C Systems with Balanced Voltages.

The longitudinal differential protection of an a-c system with balanced voltages in a single line portrayal is presented in fig. 2.8. A secondary transformer windings are included in counter-current and in series with the relay winding P. Under normal operating conditions or during a short-circuit outside the protective zone (point a) secondary voltages of the current transformer balances each other out ($E_1 = E_2$) and the current in the relay winding is close to zero. During a short-circuit in the zone covered by the protective device (point b) the balance of the secondary voltage is disrupted ($E_1 \neq E_2$), and in the relay winding the current appears. The relay operates and disconnects the system's protected sector. A break of the auxiliary conductors does not result in a false operation of the protective device.

The common fault of the above mentioned protective devices is the necessity of stringing auxiliary wires along the protected sector of the line and the presence of an operating d-c system.

Lateral differential a-c system protection in single line portrayal is presented in fig. 2.9. Each phase is split into two parallel sectors. On both ends of the sectors protected the current transformers are connected. During normal work and external short-circuits the secondary current transformers are added up (in circulating current systems), the current in the relay windings P is zero and the protection device does not operate.

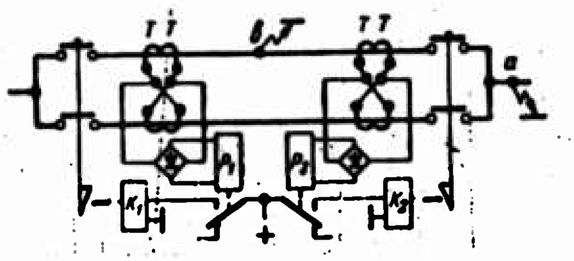

Fig. 2.9. Lateral Differential A-C System Protection.

When one circuit is shorted out in the zone covered by the protective device, the equality of currents in the transformer windings is disrupted and in the windings of relay P a current appears, the relay operates and releases the cages. The conductors disconnect the damaged sector from the system on two sides, as a result of which dead zones are excluded.

The principal short-comings of this protection in comparison with the lateral protection are its bulkiness and the increased non-balanced current.

A non-balanced current in the lateral differential protection systems may have greater values than in longitudinal protection systems, which is explained by the presence, in addition to the non-balanced current, caused by errors in the current transformer, of an additional non-balanced current component, which is determined by the inequality of the parallel lines' resistance.

The lateral differential protection system is sufficiently sensitive. In distinction from the longitudinal system, it reacts not to the full current of the short-circuit at the place of damage, but to the current difference. The sensitivity of lateral protective devices is reduced because of the unequal resistance of the parallel lines.

The reliability of lateral differential protective systems is higher than that of the longitudinal because of the absence of auxiliary conductors.

The selection of current for the operation of differential protection system is determined by the following:

1. A protection should operate reliable when there is a short-circuit in the protected zone. This signifies that the protection operation current I_{po} should be equal or smaller than the minimum short-circuit current in the protected zone. Usually for a reliable operation of the protective device it is assumed that

$$I_{po} = (0.6 - 1.3)I_{s.c.min}.$$

The minimum short-circuit current is obtained during a unilateral feed of the protected sector of the system from a single generator.

2. The protective devices should not operate during external short-circuits and normal working conditions. This signifies, that the relay operating current should be greater than the so-called non-balanced currents I_{nb}, which flow through the relay under the above mentioned contions and are caused by dissimilar characteristics of the current transformers:

$$I_{r.o} > I_{nb\ max}.$$

The non-balanced current proves, the greater, the greater is the current of the external short-circuit.

The role of the transient conduct resistances in the total resistance of the line is smaller than in the direct-current circuits, which simplifies the tune-up of the protective devices and makes it possible to raise its sensitivity.

5. Differential Protection of Three-Phase Systems with some Meters.

As it has already been noted in order to protect the three-phase system which has a regular and bilateral supply, from the viewpoint of selectivity and rapid action, the differential protection principle is used, based on the comparison of currents (or voltages proportional to them) passing through the protected sector.

The comparison of the currents in each of the phases separately, complicates protection, because of the larger number of transformers, therefore it is advisable to transform the three-phase current or voltage into a single-phase with its subsequent comparison.

The three-phase current can be transformed into one-phase current by filters of the symmetrical components or summators (the latter are simpler and therefore are more widely used). This meter is a current transformer, which adds up the magneto-multiforce of one of several phases.

In order to protect the a-c three-phase system with a grounded neutral, summators are used, in which the wires of one phase pass through the summator's window in the opposite direction, the wires of the second phase in the direct direction, and those of the third phase twice into the straight direction (see fig. 2.11).

When the summators are made identical, the vector diagram of the resulting currents of their primary windings during normal work, are identical. Here, the electro-multiforces induce by the flow of the corresponding currents of the primary windings are identical, while the resulting electro-multiforce of the counter-current connection of the secondary windings is equal to zero, and the current in the circuit of the relay P is absent.

The vector diagram of the summator's currents during normal operation and the equality of currents in all the three phases is presented in fig. 2.10, a.

Upon the examination of the short-circuits, we disregard the load currents and consider, that the current has a purely inductive nature and consequently it lags behind the corresponding electro-multiforces by 90°.

In fig. 2.10, b, we present the vector diagram of the resulting primary current in the summator with single-phase short-circuit of the phases A, B, C. In fig. 2.10, c, that of the two-phase short-circuits of phases A and B, B and C, A and C, and in fig. 2.10, d, that of the three-phase short-circuit of phases A, B, C, for the network with the a-c generator with independent excitation.

The vector diagrams indicate, that depending on the type of the short-circuit, the resulting points of the summator differ (see Table 2.1).

From the table it follows, that the lowest sensitivity is possessed by the protective device at the summators, when there is a short-circuit of the phases B and C, therefore such a short-circuit is used as the basis for calculating such a protective device.

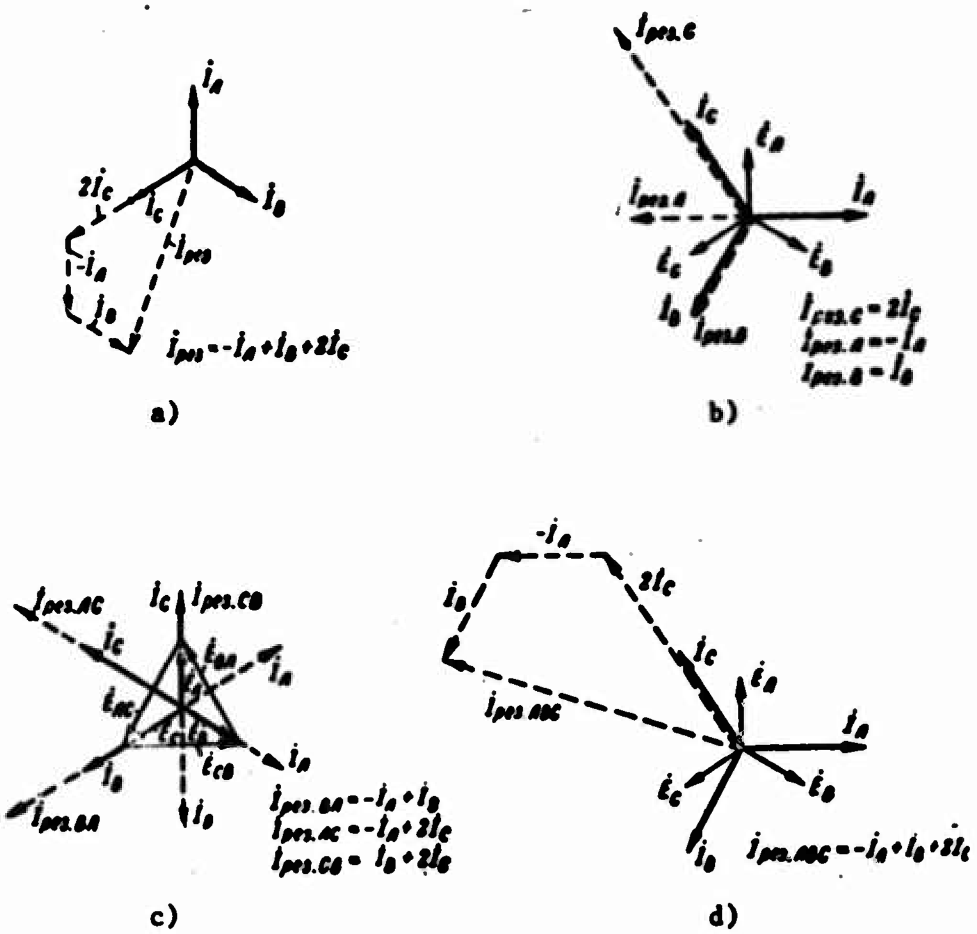

Fig. 2.10. Vector Diagrams of the Summator's Currents during Different Types of Short-Circuits.

To protect the systems with an insulated neutral, we use analogous summators, however, one phase is not introduced into the window, the two others are passed through the window in opposite directions.

Three types of protection are possible on the summators: longitudinal, lateral, and lateral-longitudinal.

The longitudinal differential protection of the system is based on a comparison of the values of currents or voltages at the output of the summators, installed at the ends of the sector protected (fig. 2.11). In the absence of damage in the zone protected, the summary voltage in the closed circuit, consisting of summator windings connected in series, connecting wires, and rectifiers supplying the winding of the relay P, is equal to zero. During a short-circuit at the sector protected, the voltage balance is disrupted, a current passes

Table 2.1

1) Виды к. з.	2) Примерное значение результирующего тока сумматора	1) Виды к. з.	2) Примерное значение результирующего тока сумматора
3) Однофазное к.з. фазы *A*	$5I_{ном}$	4) Двухфазное к.з фаз *A* и *B*	$7I_{ном}$
Однофазное к.з. фазы *B*	$5I_{ном}$	Двухфазное к.з фаз *A* и *C*	$10{,}5I_{ном}$
Однофазное к.з. фазы *C*	$10I_{ном}$	Двухфазное к.з. фаз *B* и *C*	$3{,}5I_{ном}$
	6)	Трехфазное к.з. 5)	$7{,}8I_{ном}$

1. Types of short-circuits.
2. Approximate value of the resultant current of the summator.
3. Single-phase short-circuit of phase A, B, and C.
4. Two-phase short-circuit of phases A and B, A and C, B and C.
5. Three-phase short circuit.
6. Rated ($5I_{rated}$, $7I_{rated}$, etc).

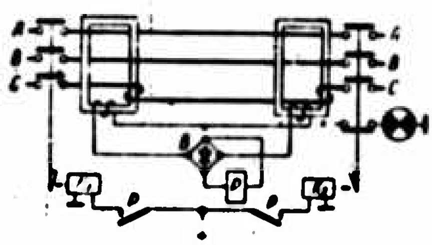

Fig. 2.11. Longitudinal Differential System Protection with Summators having a balanced Voltage.

through the relay and the line is turned off from both ends. The switching off of the conductor is signaled by means of the plug-contact which closes when it is switched off. In order to disconnect a line, when damage is present, a conductor with a latch is used, and not a conductor with a d-c retention winding. The latch eliminates the possibility of a false disconnection of the conductor upon the loss of feed caused by a break or other damage to the protection system.

In order to avoid false switching off the operational current of relay P should be greater than the current, which may originate under normal conditions, if the auxiliary connecting wires will contact one another. The tune-up of the protective device according to the lowered current, does not preserve it against non-selective action upon exterior short-circuit which is the principal shortcoming of this type of protective device.

The lateral differential system protection (fig. 2.12), the split conductors of the phases of the line protected pass through the summator window in such a way, that a voltage is induced into the winding, proportional to the difference of the currents in the phase' conductors.

In the absence of damage in the protected zone, the voltage induced into the summator's winding is equal to zero. Upon a short-circuit at the sector protected, the balance of magnetic currents is disrupted, and under the action of voltage produced, the relay disconnects the conductors on both ends of the line.

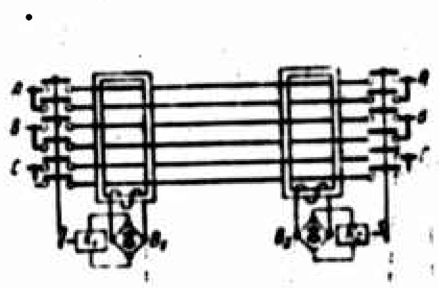

Fig. 2.12. Lateral Differential Protection of a Network with Summators (simplified diagram).

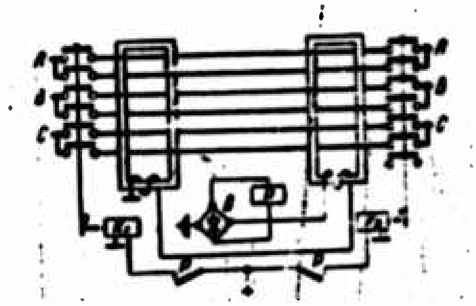

Fig. 2.13. Lateral-Longitudinal Differential Protection of a System with Summators having imbalanced Voltages.

Short-comings of the protective device lie in the possibility of false disconnection of the sector protected, which has a break in one of its split conductors, upon an external short-circuit. The smaller the length of the sector protected, the greater the non-balanced current during a external short-circuit going all the way through, caused by the inequalities of the resistances of the transient contacts.

The lateral-longitudinal protection of a system eliminates the short-comings of the longitudinal and lateral differential protective systems. A variation of the circuit diagram is presented in fig. 2.13. The substantial specific feature of the system is the fact, that the voltage at its out-put and the feed relay is absent when the connecting wires are damaged or any of the split conductors is broken.

The voltage at the summator out-put does not depend on the state of the connecting conductors and is practically equal to zero in the absence of short-circuits or breaks in the contacted sector of the system. Upon a break of one of the split conductors the voltages originating at the output of the summators, are balanced by the connecting wires.

The absence of false operation during short-circuits of secondary conductors makes it possible to use aircraft-body as a secondary auxiliary conductor.

Chapter 3. Calculation of Electrical Systems of Aircraft.

1. Specific Features of Calculation of Electrical Systems.

The electrical system is formed and calculated at all the stages of planning (draft, technical and blueprint) and construction of the experimental model. At the draft planning stage mainly a number of various variations of lay-outs of the feed system is calculated to obtain the maximum reliability and minimum weight, while the calculations of the distributing system are carried out during work planning, and refined in the process of construction and testing of the aircraft.

On the basis of technical parameters and data on the mutual position of the sources and consumers of electric energy, the places for installation of distributing systems and panels are outlined, and also for laying grounds for the power lines, indicating the length, cross-section and resistances of wires, value of the transient resistances of contact-connections and protective devices. The cross-sections of the wires are determined in accordance with the norms for the permissible rating thereof, and the minimum permissible voltages of all the energy sources and consumers under normal and emergency operating conditions.

The calculations of the electrical systems are subdivided into three types: Thermal - for the permissible load taking into account the altitude and velocity of the flight and the surrounding temperature.

Electrical - for current distribution, permissible voltage losses under the normal conditions and short-circuit currents during emergency conditions.

Spatial - for the advantageous operational current intensities and voltage losses, a minimum flight weight of the system, taking into account the parallel work of the generators. During the calculation we should take into account the number of factors:

1. Working conditions - long, brief, and repeated-brief.
2. Wire-stringing conditions - single and bunched, open and boxed conduits.
3. Conditions of the surrounding medium, location (for example on the aircraft engine), velocity and altitude of flight.
4. Cooling conditions - natural or forced air-cooling.
5. The material of the current conducting wires - copper or aluminum.
6. Conductor installations - vinyl, vinylflex, fiberglass, teflon, etc., which permit various heating temperatures.
7. Coordination of the highest current load of the wires with a type of protection: fuses, inertial, bi-metallic, differential, and other variations.
8. The heating from the stable and the shock currents of the short-circuit.
9. Voltage losses under rated, starting, and emergency conditions.
10. Parallel work of generators.
11. Power losses in the network.

When the conductors are calculated for the permissible load, their cross-section is determined, during which the heating temperature does not exceed the temperature permitted according to the norms for the type selected. From the conditions of the mechanical strength, the minimum cross-section of the wire is selected 0.35 mm^2.

In calculating the conductors for a permissible loss of voltage the minimum cross-sections of the wires is determined during which the rated work of the electric power consumers is assured under the rated, starting, and emergency operating conditions. The initial conditions in calculating the system for voltage loss are minimum voltage of energy sources, precision of the voltage regulator work, strength of the powerline, resistance of the transient conducts and minimum permissible voltage at the consumers' terminals.

In order to carry out the calculation of the network for the permissible loads and voltage stress, one has to know the current-distribution in the individual circuits of the aircraft's power system, under the possible operating working conditions of the sources and the consumers of electric power, including the emergency conditions also.

In the feed systems of simple lay-outs the current distribution among the busbars is easily found.

The problem of calculation of complex closed electrical systems generally is indefinite, because of the difficulties of finding the current distribution for the individual sectors of the closed feed systems.

Such a system is calculated by the method of consecutive approximations, that is, at first the cross sections of individual sectors of the power supply electric circuit is prescribed and the current distributions are determined. Thereupon on the basis of the current distributions found proceeding from the permissible losses of voltage, the cross-sections of the wires are determined. If the cross-sections found are near those previously selected, then the calculations end here. But if there are discrepancies, then it is necessary to prescribe new wire cross-sections and the entire calculation should be carried out anew.

In this way the calculations of complex power supply systems are carried out approximately and checked finally and adjusted according to the results of tests on the testing stands of the entire electric power system, with actual length, cross-sections, and conductor lay-out, transient conducts, energy sources, and their principal consumers. During such tests the cross sections of the conductors are rendered more precise, as are the types and the rated protection parameters.

Experience indicates, that with correct selection of the supply system lay-out and protection in the process of planning, practically after the tests on the testing stands, only the individual fuses are rendered more precise, taking into account the selectivity of operation. However, the stand tests are necessary and useful for checking the continuity of electric power supply of the consumers under the conditions of emergency situations, which are possible during the operation of the aircraft.

The calculation of emergency conditions for the power supply system is complex, labor consuming, and reflects the actual reality very closely, because it cannot take into account all the factors therefore it is carried out tentatively and with a minimum loss of time. The principal emergency conditions are checked during ground tests on a full scale testing stand.

2. Quality and Permissible Voltage Losses in the System.

The value and stability of voltages at the consumers' terminals as one of the principal factors of reliability, should be within the permissible limits under all operating conditions.

The deviations of voltages at the consumers' terminals from the normal value depend on the accuracy of the work and the point of connection of the voltage regulator and the voltage losses in the the feed and distributing network, which in their turn depend on the system of distribution of electrical energy.

As the rated voltage of the d-c generators we use the voltage equal to 28.5 v, which corresponds to the voltage at the point of connection of the operating coil of the voltage regulator, and changes in type depending on the rate of revolution of the generator, load on the system, and other factors:

$$\Delta U_g = U_{g\,max} - U_{g\,min}.$$

Carbon regulator without an attachment for precine regulation in the majority of cases assure the operating range of generator voltages of 28.5 $\pm$ 1.2 v, i. e., $\Delta U_g = 29.7 - 27.3 = 2.4$ v.

As the rated voltage at the consumers' terminals we use the voltage equal to 27 v, with a permissible deviation of $\pm$ 10%, that is,

$$\Delta U_{permiss.cons.} = 29.7 - 24.3 = 2.7 \times 2 = 5.4 \text{ v.}$$

The losses in the system are determined as

$$\Delta U_s = \Delta U_{perm.c.} - \Delta U_g = 5.4 - 2.4 = 3 \text{ v.}$$

Evidently, the voltage losses in the system without harm to the quality of the power supply may be increased by raising the work accuracy of the voltage regulator. If the voltage regulator maintains a voltage with a precision of ± 0.5 v, the permissible voltage losses in the system amount to

$$\Delta U_g = 5.4 - 1.0 = 4.4 \text{ v},$$

which accordingly assures the degrees of the systems' weight. When the former value of $\Delta U_g = 3$ v is retained, the increase in the voltage regulator's work accuracy makes it possible to raise the quality of electric power supply:

$$\Delta U_{perm.c.} = \Delta U_g + \Delta U_g = 1 + 3 = 4 \text{ v},$$

that is the voltage deviation at the consumers' terminals will be $\pm$ 2 v or $\pm$ 7.4%, which will have a telling effect on the improvement of the equipments' work, especially of the radio-engineering type of equipment.

In fig. 3.1 we show the regions of the possible voltages at the busbars of the distributing devices and the terminals of the consumers with the voltage regulator work-accuracy of $\Delta U_g = 2.4$ v, and in various electric power distributions system. From the curve it follows that:

1. In all the electric power distribution systems the voltages at the central distribution system, busbars, voltage regulator work precision, its operating coils are connected directly to the CES busbars. Consumers connected with these busbars within the limits of the working zone, can obtain the rated voltage. Since the voltage losses in the feed system are compensated by the voltage regulator, and the losses in the consumers' feeder depend only on the power consumed by it, then, if this power is constant, the selection of the conductor cross-section may assure the rated voltage of this consumer.

2. In a mixed and decentralized electric power distribution systems, at all the distributing busbars of the AZS the voltage fluctuation depends on both the accuracy of the voltage regulator's work and the number of the simultaneously connected consumers for all the busbars, therefore the quality of the consumers feed from these busbars is worse than from the primary busbars. In this way, the voltage at the consumers' terminals connected to these busbars depends on the accuracy of the voltage regulator's work, the voltage losses in the feed system and in the consumer's feeder.

3. When the voltage regulator winding is connected directly to the plus terminal of the generators, the voltage on the CDS busbars will also change in relation to the quantity and capacity of the consumers switched on.

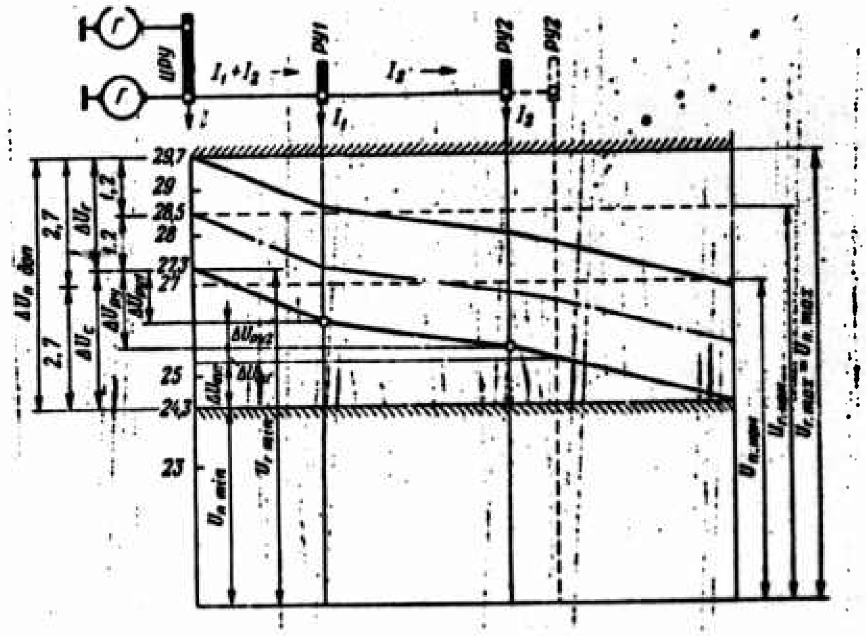

Fig. 3.1. Graph of the Distribution of the Permissible Voltage Loss in the Power Supply and Distribution Systems.

3. Calculation of the Cross-Sections of Conductors for the Permissible Loads and their Voltage Losses.

The calculation of the conductors for the permissible loads (heating) presents considerable difficulties, since the same wire may encounter different environmental conditions, and therefore, in actual practice instead of calculating the cross-section of the conductors is selected according to the permissible load tables, which are formed on the basis of the results of experimental investigations under conditions which are close to operating conditions.

For a long work regime the wire cross-sections are selected in accordance with the inequality

$$I_{permiss.} > I_{max},$$

where $I_{permiss.}$ - is the permissible current of the wire taken from the table;

I_{max} - is the highest current of the conductors' load.

In Table 3.1 we give the norms of the permissible loads to the BPVL grade conductors.

For a brief and repeated-brief working regime with the same permissible heating temperature the load on the conductor may be considered appreciably greater than is determined in relation to the time of the work according to special groups (fig. 3.2).

Copper and aluminum conductors are used in aircraft. With the same current loads and the voltage losses and use of aluminum wires instead of copper wires cuts the weight of the system in half [10]. The specific heat of aluminum is three times greater than that of copper, which makes it possible to permit a greater load on the aluminum wires under brief and repeated-brief conditions.

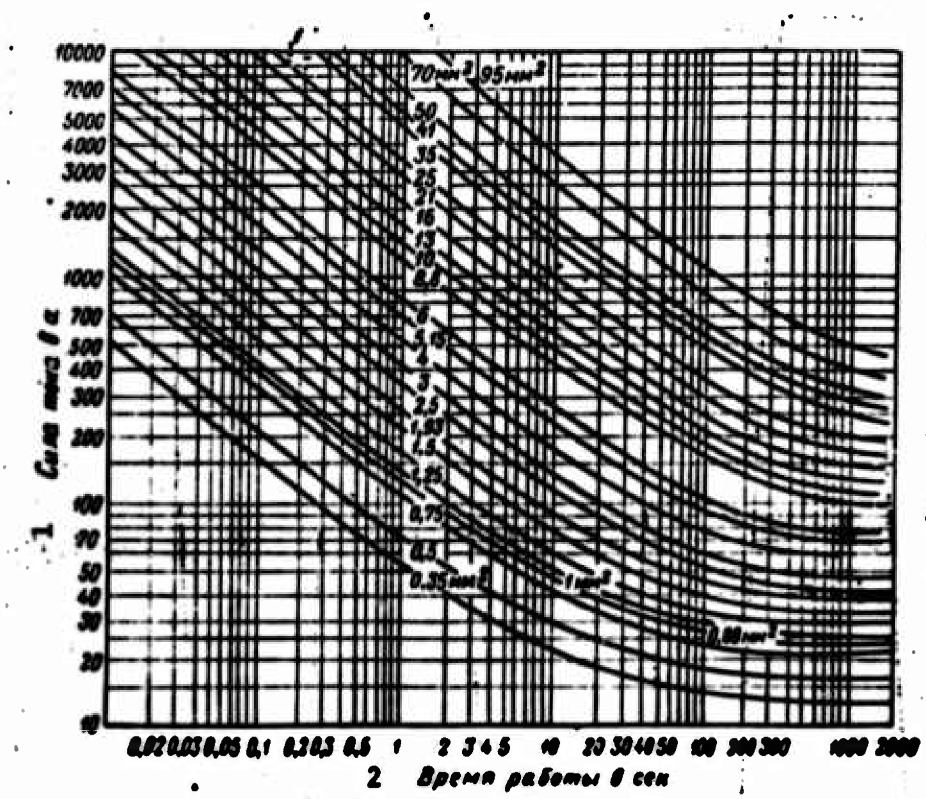

Fig. 3.2. Graph of the Maximum Overload Characteristics of freely suspended BPVL Wires at a Temperature of + 20° C in Ground Conditions.
Key: 1. Current power in amperes; 2. working time in seconds.

Table 3.1: Permissible Load Standards for Conductors of the BPVL and BPVLE Grades.

3) Сечение провода $мм^2$	1) БПВЛ и БПВЛЭ 4) Наружный диаметр мм: БПВЛ	БПВЛЭ	5) Расчетный вес кг/км: БПВЛ	БПВЛЭ	6) Активное сопротивление ом/км	7) $I_{доп}$ одиночн. провод а	8) $I_{доп}$ провод в жгуте а	9) Кратковременная перегрузка мин: 150%	200%	300%	2) БПТ и БПТЭ 10) Активное сопротивление ом/км
0,35	2,3	2,9	7,5	20	58,0	10	6	—	—	—	58,0
0,5	2,5	3,1	10,0	23,0	41,3	13	9	—	—	—	41,3
0,75	2,7	3,3	13,0	29,0	26,8	16	11	—	—	—	26,8
0,88	2,8	3,4	15,0	32,0	22,8	18	13	—	—	—	Не изготовляется 11)
1,0	3,0	3,6	16,5	33,0	20,5	20	14	0,5	—	—	20,5
1,25	3,1	3,9	20,0	50,0	16,3	22	16	0,6	—	—	Не изготовляется
1,5	3,4	4,2	23,0	61,0	13,3	25	18	0,65	—	—	13,3
1,93	3,6	4,4	30,0	62,0	10,42	30	22	0,75	—	—	Не изготовляется
2,5	3,9	4,7	35,0	68,0	8,0	35	[illegible]	0,85	—	[illegible]	8,0
3,0	4,1	[illegible]	42,0	77,0	6,[illegible]	40	[illegible]	1,0	0,5	[illegible]	Не изготовляется
4,0	4,7	5,5	50,0	86,0	5,0	48	35	1,0	0,5	—	5,0
5,15	5,1	5,9	70,0	110,0	3,88	55	40	1,3	0,65	—	Не изготовляется
6,0	5,4	6,2	72,0	114,0	3,3	60	45	1,5	0,75	—	3,3
8,8	6,2	7,0	112,0	158,0	2,4	75	56	1,8	0,9	—	2,4
10,0	6,9	8,1	126,0	196,0	2,0	82	63	2,0	1,0	—	2,0
13,0	7,5	8,7	165	237	1,5	97	75	2,3	1,2	—	Не изготовляется
16,0	8,0	9,2	178	261	1,2	110	85	2,6	1,3	—	1,2
21,0	8,9	10,1	250	335	0,96	130	100	3,0	1,5	0,5	Не изготовляется
25,0	9,5	10,7	270	360	0,8	150	114	3,3	1,65	0,55	0,8
35,0	11,1	12,3	370	477	0,57	180	140	4,1	2,0	0,7	0,57
41,0	12,0	13,2	470	597	0,49	200	155	4,5	2,2	0,75	Не изготовляется
50,0	13,0	14,2	515	634	0,4	225	175	5,0	2,5	0,83	0,4
70,0	14,5	15,7	690	815	0,29	260	220	6,0	3,0	1,0	0,29
95,0	17,0	18,2	952	1100	0,20	310	270	7,2	3,6	1,2	Не изготовляется

1. BPVL and BPVLE.
2. BPG and BPGE.
3. Conductor cross-section, mm^2.
4. Outer diameters, mm.
5. Calculated weight, kg/km.
6. Active resistance, ohms/km.
7. $I_{permiss.}$, single wire, a.
8. $I_{permiss.}$, bunched wire, a.
9. Brief overload, min.
10. Active resistance, ohms/km.
11. Is not manufactured.

In comparison with copper wires, aluminum conductors have the following shortcomings: greater cross-section, rapid oxidation resulting in the increase of resistance between conducts, one-half as large time resistance to rupture and a greater degree of mechanical strength-loss during heating.

The aluminum wires are used in power circuits of the feed systems, where they are very advantageous with respect to the weight of the system.

In calculating the electric power systems according to the permissible voltage loads, two concepts are introduced - the drop and loss of voltage. The voltage drop is the geometrical difference of the voltages at the beginning and end of the line, and voltage loss is their algebraic difference. For the direct-current these two concepts coincide. The value of the voltage loss in a d-c line is determined by the sum of voltage drops in all the resistances (R) through which current (I) flows:

$$\Delta U = I \cdot \sum_{k=1}^{n} R_k.$$

With the same value of the power and voltage transmitted, the current in the a-c system is $\frac{1}{\cos\phi}$ greater than the current in the direct-current system, therefore, the calculation of the a-c system should be carried out proceeding from the four (apparent) current.

The voltage loss in the a-c line is determined by the expression

$$\Delta U = I(R \cdot \cos\phi + X \cdot \sin\phi) = I_a R + I_p X,$$

where I - is the full current;
R and $X = \omega L$ - are the active and reactive resistances of the line.

The inductivity for the two-conductor line

$$L = \left(0.92 \lg \frac{A}{r} + 0.1 \right) \cdot 10^{-3} \text{ H/km},$$

where A - is the distance between the conductors;
r - is the wire radius.

For the single conductor line, instead of A we take the double distance of the wires from the aircraft-body.

The inductivity of a single phase of a three-phase line is expressed as

$$L = \left(0.46 \lg \frac{A_{cp}}{r} + 0.05\right) \cdot 10^{-3} \text{ H/km}.$$

The mean geometrical distance between the conductors

$$A_{cp} = \sqrt[3]{A_1 \cdot A_2 \cdot A_3},$$

where A_1, A_2, A_3 - are the distances between the corresponding phase conductors.

During approximate calculations of the network, the reactive resistance of the conductors to alternating-current is assumed to be equal to $(1 \div 2) \cdot 10^{-3}$ ohms/m.

Transient resistances of contacts have a substantial effect on the voltage losses in the system. This is especially felt when the large section wire and the body of thc aircraft are used as one of the conductors. The exact estimation of the transient resistant is difficult, therefore in calculating the approximate, we adopt the values given in table 3.2.

In calculating the system, it is common practice to draw the diagram in a one-line portrayal. For the two-line transmission system, in order to take into account the resistance of the diverse wires, the length of the line calculated should be doubled. With a one-line diagram the resistance of the reverse wire (aircraft body) may be disregarded.

The calculation of the system is started with a preliminary determination of the current distribution of the noted points. The

Table 3.2: Transient Resistance Values

1) Тип контактного соединения	Величина переходного сопротивления 2) *ом*	Тип контактного соединения 3)	Величина переходного сопротивления 4) *ом*
5) Болтовое соединение	$(0,5-1,0)\,10^{-3}$	9) Автоматы защиты	$(0,9-52,7)\,10^{-3}$
6) Штепсельное соединение	$(0,15-2,5)\,10^{-3}$	10) Инерционные предохранители	$(0,15-1,4)\,10^{-3}$
7) Контакты контакторов	$(0,32-0,64)\,10^{-3}$	11) Тугоплавкие предохранители	$(0,03-0,34)\,10^{-3}$
8) Контакты реле и выключателей	$(3,0-15,0)\,10^{-3}$	12) Плавкие предохранители	$(1,2-26)\,10^{-3}$

1. Type of conduct connection.
2. Value of transient resistance, ohms.
3. Type of conduct connection.
4. Value of transient resistance, ohms.
5. Bolt connections.
6. Plug connections.
7. Conductor contacts.
8. Relay and Switch-contact.
9. Automatic protective devices.
10. Inertial cut-offs.
11. High-melting fuses.
12. Fuses.

system is conventionally reduced to a radial system with concentrated loads over the distributing busbars. Further, according to the known values of currents I, wirelength l and permissible voltage drops $\Delta U_{permiss}$. the wire cross-sections S are determined for each sector of the system.

For the direct-current

$$S = \frac{I_l}{\gamma \Delta U'_{permiss.}},$$

where $\Delta U'_{permiss}$ - is the calculated permissible voltage loss in the conductor;

I - is the load current;

$$\Delta U'_{permiss} = \Delta U_{permiss} - \Delta U_k ,$$

where $\Delta U_{permiss}$ - is the total permissible voltage loss of the systems' sector calculated;

ΔU_k - is the voltage loss in the transient conducts of the system.

For alternating current with a small length of the powerline the inductive resistance may be disregarded. Then we shall have:

$$S = \frac{2Il}{\gamma \Delta U'_{perm.}} \cos\phi$$ - for single phase current;

$$S = \frac{\sqrt{3}Il}{\gamma \Delta U'_{perm.}} \cos\phi$$ - for three-phase current, where I is the apparent current.

From the formulas it is obvious, that in the transmission of the same power in the single-phase a-c system, the total voltage loss is equal to the double voltage loss in the single wire, and in the three-phase current system with the uniform load, it is only 1.73 times greater than the voltage loss in a single wire. This is explained by the fact that with a uniform load of the three-phases the current in the zero-wire is absent. With a nonuniform load of the three-phase system in the zero-wire a current will flow, but the voltage loss in it may be disregarded, since the body of the aircraft serves as the zero conductor.

If in the calculation we have to take into account the inductive resistance of the conductor, then $\Delta U'_{perm}$ is assumed to be decreased by the volume of the voltage loss in the active resistance, i. e., by the value of I_pX.

If we replace the current power I by its value

$$I = \frac{P}{U\cos\phi}$$ - for single phase current;

$$I = \frac{P}{\sqrt{3}U_p\cos\phi}$$ - for three-phase current,

and express ΔU in percent of U, i. e.,

$$\Delta U = \frac{\varepsilon U}{100},$$

where U - is the voltage in the consumers' terminals;

ε - is the voltage loss in %,

then finally:

$$S = \frac{2Pl}{\gamma\varepsilon U^2}\,100 = \frac{200Pl}{\gamma\varepsilon U^2} \text{ - for single phase current;}$$

$$S = \frac{Pl}{\gamma\varepsilon U_p^2}\,100 \text{ - for three-phase current.}$$

From the formulas we can see that the conductor cross-section is inversely proportional to the square of the voltage, therefore, in order to increase the conductor cross-section (reduction of weight) it is recommended to raise the voltage.

4. Effect of Voltage Regulation Precision on the Calculation of the Feed System.

In planning power systems, we should examine a number of inter-related factors: reliability, minimal weight, precision of voltage regulation, complexity of regulating equipment, lay-out, channels, and protection of the feed system, as well as the rationality of distributing devices, busbar-loads.

The voltage regulation precision makes it possible to decrease substantially the weight of the network to the increase of the voltage drop permissible in it, but the precision increase is rational up to a certain point, i. e., up to the moment when it is accompanied by an improvement in the system's conductor weight. Depending on the type of the aircraft, the lay-out of the distribution system, and the current load on the distributing device busbars, we determine the optimum precision of the voltage level regulation, which assures the minimum weight of the electric power system.

The increase of the voltage regulation accuracy above the optimum, does not yield a decrease in the weight of the feed system wires, but results in a structural complication of the regulating equipment, and in the reduction of the work of the entire electric power system.

If the voltage regulation accuracy is not taken into account, or is used incorrectly in the calculations of the rated and emergency conditions of the work of the feed system, this results in a sharp decrease of the service life of the consumers, and sometimes because of poor quality of the electric energy supply, they are put out of commission.

By the emergency operating conditions of the feed system, we understand the failure of one or several lines of a multi-channel system. Upon the failure of a single line the quality of the supply to the consumers should not deteriorate substantially, and only during a second case of damage to the power supply system in the same sector, the electric energy consumers which are supplied from the given distributing system, receive electric power of a lower quality.

For such electric power systems the maximum permissible voltage drop in the feed system will be determined as

$$\Delta U_{\text{ру max}} = U_{\text{г min}} - (U_{\text{п min}} + \Delta U_{\text{ф.п}} + \Delta U_{\text{ф.г}}), \tag{3.1}$$

where $U_{c\ min}$ – is the minimum permissible voltage on the consumers' terminals;

$\Delta U_{f\ c}$ – is the voltage drop at the consumers' feeder;

$\Delta U_{f\ g}$ – is the voltage drop at the generators' feeder (from the point of connection of the voltage regulator to the primary distributing busbar).

If the electric power system is designed without taking into account the failure of the feed lines, then the given maximum voltage drop should be considered as the calculation drop.

If in designing the electric power system we take into account the possibility of failure of a part of the feed lines, then the calculated voltage drop will be

$$\Delta U_{\text{ру.расч}} = \Delta U_{\text{ру.max}} \cdot \frac{n-k}{n}, \tag{3.2}$$

where n – is the total number of feed lines, passing to the given distributing device;

k – is the number of lines put out of commission.

The cross-section of the wires supplying the distributing device is determined by the expression

$$S_{\text{расч}} = \frac{Il}{\gamma n \Delta U_{\text{ру.расч}}}, \tag{3.3}$$

where I – is the current at the DS busbars in ampere;

l – is the distance from the center of the distributing system to the through the distributing system in meter;

γ – is the specific conductivity of the conductor in meter/Ω-mm^2.

Further, according to the wire table, we adopt the nearest, greatest standard cross-section $S_{table} > S_{calc}$, which is checked according to the permissible current load under emergency conditions of the supply system work:

$$I_{permiss} > \frac{I_{py}}{n - k}, \tag{3.4}$$

which guarantees the working capacity of the conductor under emergency working conditions of the distributing system.

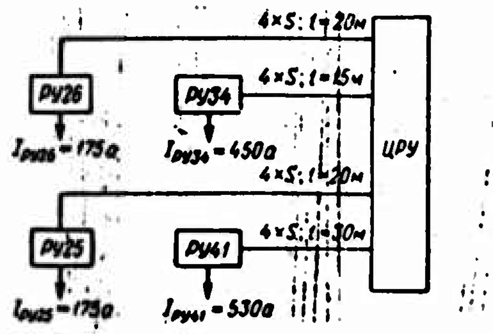

Fig.3.3. The calculation diagram of the feed system.

From expressions (3.1) and (3.3) we can see that the increase of accuracy in regulating a prescribed voltage level (increase of the minimum generators' voltage) makes it possible to reduce considerably the weight of the feed per system to the increase of the permissible voltage drop in it. This will occur until the calculated wire cross-section will be limited by the maximum permissible current load.

In this way, in order to create a system of electric power supply with minimum weight, it is required to string the wires in accordance with their permissible current load. This is possible, even if the voltage level regulation accuracy assures the required voltage drop in the supply sytem.

Let us determine the effect of the voltage level regulation precision on the weight of the supply system, the calculated diagram of which is given in fig. 3.3.

In accordance with the norm, we assume that the rated voltage of the generators (point of connection of the voltage regulator) we use,

$U_{g\ rated}$ = 28.5 v, the voltage drop in the generator feeder $\Delta U_{f.g}$ = 0.3 v, in the consumers' feeder $\Delta U_{c.f}$ = 1.0 v, and the voltage at the consumers' terminals U_c = 27 v ± 10%, i. e., $U_{c\ min}$ = 24.3 v; $U_{c\ max}$ = 29.7 v.

As the precision of voltage regulation we adopt the value ΔU_p = $U_{g\ max} - U_{g\ min}$, which in the existing regulators lies within the bounds of ± (1.2 - 2.0)v. In this case the upper limit of the generators' voltage equal to 30.5 v, exceeds the value of permissible force for the consumers, which does not exclude the possibility of overvoltage of the consumers, when they are turned singly. However, during flight the over-voltage is practically little probable, because of the voltage drop in the system. The case examined, the lower voltage level is important, which is the determining value for the weight of the network upon the airplane.

When the regulation precision is ΔU_r = 0 the maximum permissible voltage drop in the feed system

$$\Delta U_{ds\ max} = 28.5 - (24.3 + 1.0 + 0.3) = 2.9\ \text{v}.$$

The calculated voltage drop when one line goes out of order is

$$\Delta U_{ds\ calc} = 2.9 \cdot \frac{3}{4} = 2.18\ \text{v}.$$

For the distributing busbar of DS25

$$S_{m\ calc} = \frac{175 \cdot 20}{50 \cdot 4 \cdot 2{,}18} = 8.05\ \text{mm}^2.$$

We select according to the table the closest rated standard cross-section

$$S_{m\ table} = 8.8\ \text{mm}^2,$$

which we check according to the current load

$$I_H = \frac{175}{3} = 58.33\ \text{ampere},$$

and an 8.8 mm^2 conductor sustains 56 amp., therefore, we finally adopt the cross-section $S = 10\ mm^2$. The weight of the main lines will amount to

$$G_m = 4 \cdot p \cdot 1 = 4 \cdot 0.126 \cdot 20 = 10.1\ KH.$$

We shall make an analogous calculation for aluminum conductors

$$S_{a\ calc} = \frac{175 \cdot 20}{34 \cdot 4 \cdot 2{,}18} = 11.8\ mm^2.$$

We select on the table $S = 35\ mm^2$, which can hold up under the permitted current load.

Then the weight of the main lines will amount to

$$G_{a\ con} = 4 \cdot p \cdot 1 = 4 \cdot 0.131 \cdot 20 = 10.5\ KH.$$

Thereupon we carry out calculations for DS25 with various regulation precisions. Analogously we calculate the cross-sections and weight of the conductors of other DS, and put the various calculation results down onto the table.

Let us determine the optimum of precision of voltage regulation of the DS for aluminum wires, selected according to the permissible current load.

For DS25 and DS26

$$\Delta U_{ds\ calc.} = \frac{175 \cdot 20}{34 \cdot 4 \cdot 35} = 0.74\ v;$$

$$\Delta U_{ds\ max} = 0.74 \cdot \frac{4}{3} = 0.985\ v;$$

$$U_{g\ min} = 0.985 + 25.6 = 26.585\ v;$$

$$\Delta U_{ds25,26} = 2(28.5 - 26.585) = 3.83\ v.$$

By an analogous calculation for distributing systems 34 and 41 we get:

$$\Delta U_{DS34} = 3.91 \text{ v};$$

$$\Delta U_{DS41} = 2.5 \text{ v}.$$

The voltage level regulation precisions obtained are optimum for their distributing systems. The optimum value of the regulation precision for the entire power network aboard the aircraft will be the value of $\Delta U_p = 2.5$ v, which is the highest in the given distribution system, which satisfies the consumers, which are supplied from any distributing device.

The application of the regulation precision on a given aircraft above the optimum precision is not expedient, since it does not yield any advantage in weight of the power supply system with the normal amount of energy.

From the above it follows:

1. In planning the electric power supply systems on heavy aircraft, it is necessary, in addition to the general load schedule, to combine load schedules for the distributing system busbars. With the correct distribution of the loads over the busbars, the optimum voltage level regulation precision for the entire power system is at the same time rational for any distributing system, which provides a minimum weight for the power supply system.
2. For every type of aircraft there is an optimum value of voltage level regulation precision, which provides all the consumers with electric energy of satisfactory quality with a minimum weight of the power supply system.
3. The use of voltage regulators with a regulation precision above the optimum renders the design of the voltage regulators more complicated and reduces the reliability of the power supply.
4. The weight of the supply system increases increases not gradually, but in jumps, because of the large intervals in the wire cross-section scale.
5. It is not advisable to use copper wires with cross-sections more than 10 mm^2, out of weight considerations. Aluminum wires should be used.
6. In calculating the power supply system it is necessary to take into account the possibility of failure of the power supply line, of the distributing devices. For busbars, supplying important consumers, the voltage should not drop below the permissible value, when one channel goes out of commission.

Having determined the maximum current loads of the distributing system, we can calculate their maximum permissible distance and the maximum permissible current moments with various precisions of the voltage level regulation.

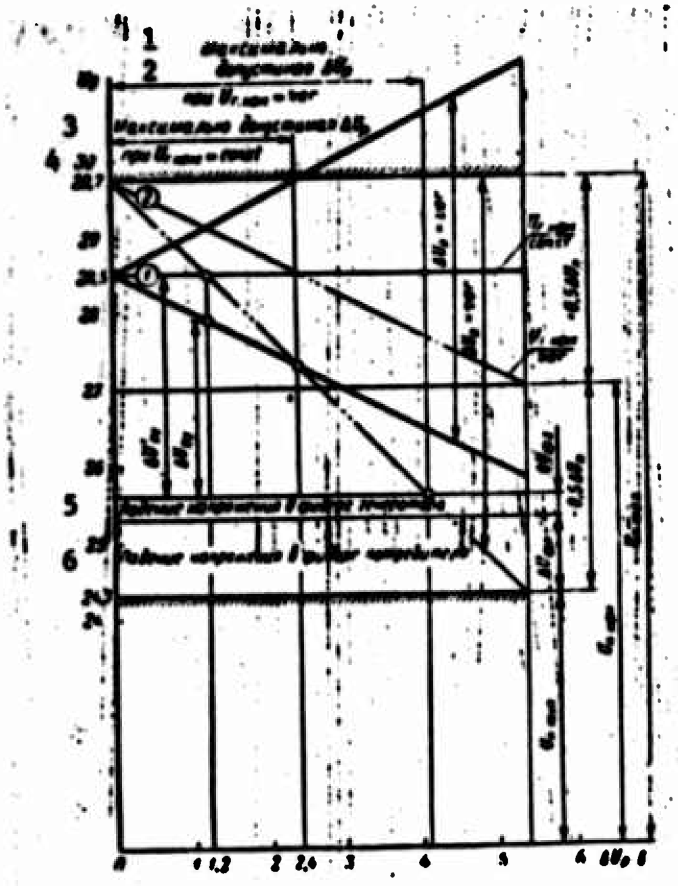

Fig. 3.4. Permissible voltage loss curve in the power supply system in relation to the law and the voltage regulation precision.
Key: 1. Maximum permissible ΔU_p; 2. with U_g nominal = variable; 3. maximum permiss. ΔU_p; 4. with U_g nominal = constant; 5. voltage drop in generator feeder; 6. voltage drop in consumer's feeder.

In fig. 3.4 we show the graph of permissible voltage losses in the power supply system in relation to the regulation accuracy under two laws, with a constant one, and a "floating" 2 nominal.

Today the rated voltage, maintained by the voltage regulators, is adopted as equal to $U_{g.nom.} = 28.5$ v, with the regulation law

$$U_g = U_{g.nom} \pm 0.5\ \Delta U_p. \tag{3.5}$$

The factors determining the use of voltage regulators with such a regulation law, are the values of the maximum and minimum voltages. It is quite dangerous to use voltage regulators, which permit a $U_{g\ max} > 29.7$ v, since when the single consumer is switched on, it can go out of commission because of the high voltage in the power lines aboard the aircraft. The low minimum voltage makes it necessary to string wires of large cross-sections, resulting in a considerable increase in the weight of the power supply system. The modern heavy aircraft with the distributing systems, located at distances of 30 to 35 m, and current moments of 20,000 - 22,000 amp. m, require for the creation of d-c minimum weight power systems, a voltage level regulation precision of $\Delta U_p \approx 1$ v.

Let us examine another regulating method, namely the method of the "floating" nominal voltage, according to which the nominal voltage is not constant, but changes in relation to the voltage level regulation precision. In this case the upper limit of voltage remains unchanged, equal to 29.7 v, with any voltage regulation accuracy. In this case

$$U_{g\ min} = U_{g\ max} - \Delta U_p \ldots \tag{3.6}$$

Regulating the voltage according to the "floating" nominal method within the regulation precision limits from 0 to 2.4 v ($\Delta U_p = 0\ -2.4$ v) the value of the minimum generator voltage is greater, than with regulation according to the constant nominal method. With the value of $\Delta U_p = 1.2$ v, the method of the "floating" nominal voltage makes it possible to obtain the same reduction of the weight of the power supply system, as with $\Delta U_p = 0$, according to the constant nominal method.

As we can see from the curve in fig. 3.4, from the point of view of the minimum weight of the power supply system, it is more advisable to regulate the voltage according to the law of "floating" nominal within the bounds of $\Delta U_p = 0 - 2.4$ v, while in regulating according to the constant nominal law, in order to obtain the same effect, an increase in precision is required. The transmission of such current moments has 20,000 - 22,000 amp. m, using the "floating" nominal method in regulators, may be assured by voltage regulators with the regulation accuracy of $\Delta U_p \approx 1.8$ v.

The optimum voltage level regulation precision in the power system aboard the aircraft is determined by the necessary accuracy in regulating any one of the distributing devices and may be 1.5 to 2 times greater than the required regulation precision for other distributing devices. This results in the necessity of using voltage regulators with a higher regulation precision.

In planning the power system we should strive to distribute the loads between the distributing systems, so that they would have an equal value of the required regulation precision. If however, the regulation precision has been prescribed ahead of time, then, using the current moment curves and distributing system load curves, we should distribute the load between them in such a way, that the prescribed regulation precision would be optimum for all the distributing systems of the aircraft.

Since the arrangement of the distributing systems is determined by the general lay-out of the aircraft, the distance at which they are located is prescribed ahead, therefore, in order to assure the minimum weight of the d-c power system, it is necessary to determine the current moments of the distributing systems and according to their known distance determine the permissible current loads with various voltage level regulation precisions.

5. Calculation of Short-Circuit Currents of an Electrical System.

The short-circuits of conductors may be dead or intermittant. In power circuits damage is accompanied, as a rule, with dead short-circuits, which are characterized by 0 resistance values at the short-circuit point.

In as much as a short-circuit is a serious type of damage to the electrical system, it should be quickly isolated from the part of the system which is good working order, by means of protective devices. In order to select correctly the protection and switching equipment, which is able in the case of a short-circuit, to switch off the faulty sector of the system, it is necessary to know the currents and voltages of individual sectors of the system during a short-circuit. It is necessary to know the value of short-circuit currents also, in order to determine the dynamic forces and thermal loads of the elements of the electric power system.

The short-circuit currents are calculated by the graphical or grapho-analytical method.

In the graphical method the values of a current and voltage during a short-circuit are determined graphically according to the volt-ampere characteristics of the sources and consumers of electric energy.

The value of the short-circuit current is affected by a number of factors: The quantity of sources and consumers connected in parallel, the character of their volt-ampere characteristics, the place and type of short-circuit, the lay-out of the power supply system, the transient resistances in the connections, protection system, contacts, and other equipment, the exact effect of which it is practical impossible to estimate.

Therefore, the calculation results have an approximate character with a precision of 10 - 15%. This precision is sufficient for a practical concept of the order of the possible values of short-circuit currents.

More precise data may be obtained in testing natural size models of energy systems under laboratory conditions, however, even in this case the short-circuit processes, and their consequences will differ from the actual ones.

In calculating short-circuit currents in d-c systems, we examine and establish short-circuit regime, while the volt-ampere characteristics are selected for the generator during the maximum revolution velocity, for the battery which is fully charged (not less than 75%) and for the rated load current.

In fig. 3.5 we present the diagram of a system with a single generator, the external characteristic of the generator, and the graphic method of calculation of established short-circuit current. Let us assume, that at a certain distance from the generator at point a, there is a short-circuit with a constant resistance r_K, which may be considered as a consumer.

If we disregard the resistance of the line between the source and point a, then the voltage of the source and consumer are r_K, and the point examined will be equal, and consequently, the value of the current and short-circuit voltage at this point are determined by the abscissa and alternate of the point of intersection of the external characteristics of the generator (curve 1) and the resistance beam r_K.

In order to take into account the voltage drop in the line from the generator to point a, we draw a resistance beam of this line, R'_1. And then from the external characteristics of the generator, we graphically subtract the straight line IR'_1 and obtain the external

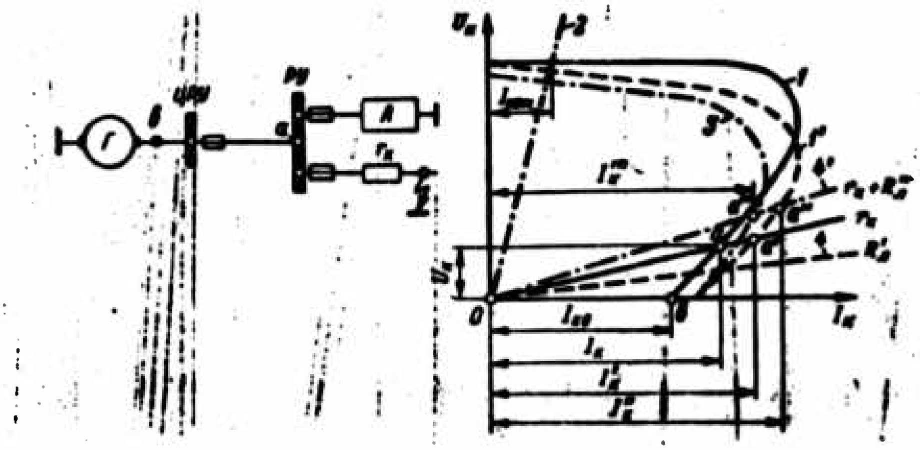

Fig. 3.5. Calculation of the steady short-circuit current with power supply from one generator with a type A load.

characteristic of the generator, reduced to point a (curve 1'), the intersection of which is beam r_{κ} equals the short-circuit current I'_{κ} (point a').

In order to estimate the voltage drop in the line from the resistance $r_{\kappa H}$ to point a, we plot the resistance ray of this line R''_1, which is added up with ray r_{κ} and use a volt-ampere characteristic of the consumer with an allowance for the voltage drop in the line (ray 4'). The intersection of characteristics 1' and 4' (point a") yields a short-circuit current I''_{κ}.

To estimate the effect of volt-ampere characteristic of the load it is necessary for each given voltage to subtract the current of the load's volt-ampere characteristic (ray 2) from the current of the generator's external characteristic (curve 1'). The resulting curve 3 is the reduced volt-ampere characteristic of the generator, the intersection of which with ray 4' yields the short-circuit current I''_{κ}. With the short-circuit at the generator terminals ($r_{\kappa} = 0$), the short-circuit current $I_{\kappa 0}$ does not depend on the value of the load R_H (point b).

In fig. 3.6 we present the graphic calculation of a stabilized short-circuit current when the power system is supplied from two generators and a storage battery.

At first the volt-ampere characteristics of the source are brought up to point b. In this case we take into account a voltage drop in the corresponding feeders.

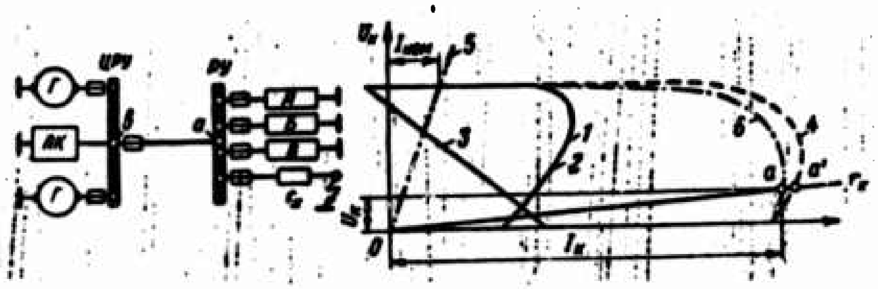

Fig. 3.6. Calculation of stabilized short-circuit current during power supply from two generators and storage battery, with consumers of the A, B, and C type.

Curves 1, 2, and 3, are volt-ampere characteristics of the generators and storage battery, brought up to point b.

The volt-ampere characteristics obtained are added up. The resulting volt-ampere characteristic is brought up to point a, taken into account the points of lines' resistance (curve 4).

Curve 5 is the total volt-ampere characteristic of loads A, B, and C.

The graphic subtraction of characteristics 5 and 4 yields a volt-ampere characteristic (curve 6) of the sources with an allowance for the load, brought up to point a.

The value of the stabilized short-circuit current is determined by the intersection of curve 6 and ray r_K at point a.

From the above it is obvious that with other conditions being equal, the short-circuit currents in the presence of the consumers connected, are smaller than in their absence. During flight it is hard to foresee, which consumer will be turned off at the moment of short-circuit, therefore, in practical calculations the influence of the consumers on the short-circuit value is ignored. In this case the short-circuit current values are somewhat over-estimated.

Section IV. Primary Direct Current Electric Power Systems.

Chapter 1. General Information on Direct Current Electrical Power Systems.

1. The Role of the Primary Direct Current Power System.

The primary electric power's d-c systems with a 27 voltage, have become widely used in a series of aircraft types, and are the principal electric power supply systems, which provide feed for consumers under normal and emergency flight conditions. The system is most rational if the consumed power of the electric energy does not exceed 9 - 12 KW per engine, and the engines are started with starter generators.

As the main sources of energy, the d-c generators are used, the total capacity of which is a selected source to provide a reserve of 50 to 100% of the total capacity of consumers operating for a long period of time.

The rated voltage of the generators is assumed to be 28.5 v ± 3% with an ordinary regulation and ± 2% v with voltage regulation, and the rated voltage of the consumers is 27 v ± 10%.

In parallel with the generators the storage batteries are corrected, which are reserve energy sources for supplying vitally important consumers which are necessary for landing or a specific flight time when all the generators have failed.

2. Principal Technical Demands on the D-C Power Systems.

The technical demands to the electric power supply systems and electric power lines apply entirely to the d-c electric power systems.

The technical specifications shall have answers for the following specific questions:

Purpose, working conditions, equipment assortment, principal parameters (power, voltage, and positions), quality of energy (permissible voltage deviations from the normal values); excitation systems, voltage regulations, control, protection, checking and working systems;

Permissible generator load irregularities with parallel work, permissible generator loads on the ground without forced air circulation and overloads during flight for 5 min and 5 sec;

Work without fail, vitality, independence, convenience and safety of service, minimum weight and dimensions;

High mechanical, electrical and thermal sinks, fire- and explosion-safety; rapid action, absence of interferences with radio equipment and magnetic instruments, simplicity, interchangeability, and sufficiently long service life.

Let us note several measures and ways of meeting the above mentioned demands:

1. Parallel work of all the sources for the main supply system.
2. Automatic connection of energy sources to the feed network at the begin of operational working conditions.
3. Automatic disconnection of energy sources from the power supply systems when the input voltage drops below the permissible limit.

4. Minimum load discrepancy between generators working in parallel (not more than 5 to 10% of the rated capacity of one generator).

5. Stable, parallel work of the generators upon the increase of the load from 0 to the rated load and decrease from the rated load to 0 (3 to 5% of the rated load).

6. Independent and selective disconnection of the energy source from the power supply system when it goes out of commission.

7. Automatic and selective disconnection of the power source from the power supply system upon a short-circuit at the "source-power supply system" sector and during overloads.

8. Automatic disconnection of the over excited generator from the power supply system, since when the operating coils of the regulator break, the voltage of the generator increases up to 50 v.

9. Retention of the working capacity of the power supply system when individual energy sources go out of commission, until at least one of them still exists.

10. Maximum reliability of the equalizing circuit, because a break in it disrupts the normal load distribution between the generators.

11. The electrical circuits of regulation, guidance, and control should have selective protective systems, providing the disconnection of the damaged line during a short-circuit and maintainance of the vitality of the remaining system.

3. Cooling of Direct Current Generators.

In the ordinary direct current generators operating up to an altitude of 18 km under subsonic flight conditions (M = 1.3), the forced cooling (blowing) with the counter current of air is used, the airstream coming into the generator under the dynamic thrust effect.

The generator calculated for forced cooling with work without blowing (under ground conditions), reduces its specific capacity by 3 to 5 times.

The increase of flight altitude over 18 km causes a reduction in the generators' capacities because of the decrease of density and weight flow rate of the air through the machine and the heat transfer coefficient of its active parts. Even a small increase of altitude results in a considerable increase of the weight of the generators in the cooling system (by 1.5 times upon the increase of the altitude from 17 to 21 km).

The increase of the flight velocity results in a decrease of the usual generator capacity, because of the rise of the cooling air temperature through its breaking action (thermodynamic heating). The thermodynamic heating of air is insignificant at subsonic flight velocities, and increases sharply upon exceeding "the sound-barrier" reaching about 250°C at a flight velocity of V_n = 3000 km/hour.

The supersonic flight velocity causes great expenditures of the aviation engine capacity for blowing air through the generators. When V_n = 3000 km/hour these losses exceed by several times the rated capacity of the machine.

The boundary of rational increase of air consumption is the so-called air-"saturation" of the machine, after which with the growth of air consumption the load cannot be increased. The increase of the temperature of the machine's active parts beyond air-"saturation" occurs approximately according to the linear law in relation to the temperature of the incoming air.

In connection with this, the necessity arose of using new principles of cooling and designing aviation electrical machines.

At high altitudes in an supersonic aircraft, d-c generators with an operative cooling are being used.

The structural systems of generators with air-operative cooling differ little from the systems with ordinary air-cooling. The role of the air is reduced to transportation of the fluid into the machine in a dispersed state. The fluid is atomized in the active part zone.

The active parts of the generators are cooled by evaporation of fine fluid films on them. The formation of films is based on the principle of centrifugal atomization of fluid. Depending on the rate of rotation, the redistribution of fluid between the winding and surface of the collector, is reached by means of the cone-type atomizer.

The intensity of film cooling is higher than the air-cooling intensity which makes it possible to decrease the outside dimension in weight of the machines by up to 30%.

The greatest interest is represented by the universal cooling system, in which in relation to the flight conditions the cooling system is switched over from air to air-operative, or purely evaporative.

The automatic conversion from one cooling system to another makes it possible to provide for the greatest effectiveness of the use of the electric machine in the aircraft with a large range of speeds and altitudes.

Chapter 2. Direct Current Energy Sources.

1. Aviation Storage Batteries.

The storage batteries are galvanic batteries in which the electrochemical processes are easily performed, i. e., the elements may give electric energy to the external circuit or accumulate it if it is delivered from a external current source.

Storage batteries, installed on aircraft, work parallel with the generators for the common power system and are intended for:

Covering the current peaks which exceed the maximum permissible load of the generators, in starting, under brief work of high capacity consumers during flight;

Energy supply to vitally important consumers in flight when the generators goes out of commission;

Energy supply to consumers during cruising over the airfield, with switched-off generators;

Feeding starters during independent starting of aircraft engines or power units;

Power supply to small capacity consumers when parked during the performance of the preflight and postflight examination in case of absence of airfields' energy sources.

The storage batteries have symbols in the forms of digits and letters, which serve for indicative numbers of cells, the rated discharged capacity (ampere hours) and type of the battery. The figures indicate: the first ones, the number of cells in the battery, the second the rated capacity of the battery discharge in 10 to 5 hours.

Several types of batteries have been adopted in aircraft: acid (lead) of the 12-A-30, 12-CAM-28, 12-CAM-53; alkaline (silver-zinc) of the 15-SZS-45; alkaline (cadmium-nickel) of the 20-KNB-30 type.

The storage battery should operate normally at all flight velocities, different maneuvers and positions of the aircraft in space, variations of surrounding temperature between +50 to -60°C (with measures taken for cooling or warming them) and atmospheric pressures of up to 25 mm of mercury.

The electro-motive force of the storage battery depends on the density and the temperature of the electrolyte and is determined with sufficient approximation by the following equation

$$E_a = 12(0.84 + d)v,$$

where d – is the density of the electrolyte at 15°C in g/cm^3.

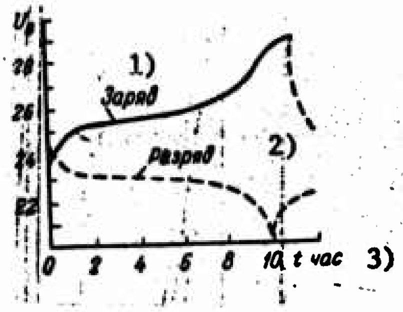

Fig. 2.1. Measurement of the storage battery voltage during charging and discharging.
Key: 1. charging, 2. discharging, 3. hours.

The internal resistance of the battery decreases during charging and increases during discharging with especially large currents. It is very small, amounting to hundredths or thousandths of an Ω, which makes it possible to obtain large currents with relatively small losses inside the battery.

The voltage of the battery differs from the e.d.f. by the values of the voltage drop in the internal circuit of the battery: during charging $U_C = E_a + I_a R_a$; during discharging $U_p = E_a - I_a R_a$, where

I_a - is the current flowing to the battery during charging and discharging;

R_a - is the internal resistance of the battery.

In fig. 2.1, we show the typical curve of voltage changes in the battery in time during charging and discharge with a current of a 10 hour regime, which for the majority of the batteries is accepted as rated.

In fully charged batteries with the electrolyte density of 1.285 g/cm^3, the electro-motive force of the battery is equal to 25.5 - 26.0 v.

In actual practice the battery discharge may be carried out only up to a certain voltage, the discharge being below which results in damage to the battery. The mode of operation for large discharge currents permits smaller final voltages.

The temperature of the electrolyte has a substantial effect on the voltage during discharge and charging of the batteries. As the temperature goes down, the viscosity of the electrolyte and the internal resistance increase, the leveling off of the density is slowed down, and the voltage drop during the passage of the current increases. The voltage at the battery terminals for the same discharge current with the decrease of the temperature, drops very steeply (fig. 2.2).

When the electrolyte freezes, the electro-motive force of the battery is practically equal to 0. Charging at a lower temperature requires a higher charging voltage.

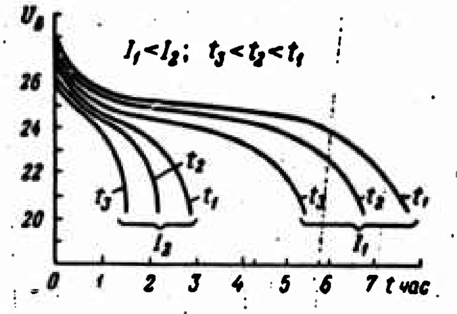

Fig. 2.2. Change in the battery voltage during discharge under various temperature and current conditions.

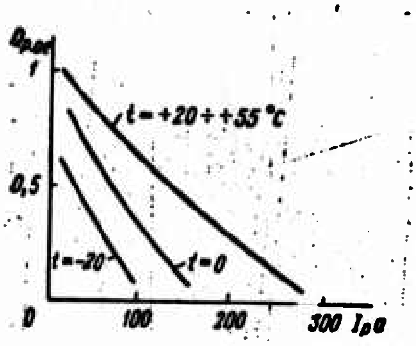

Fig. 2.3. The dependence of the battery capacity on the discharge current at different temperatures.

The capacity of a battery is determined by the amount of electricity, which it gives up during discharge down to the lowest permissible voltage:

$$Q_p = \int_0^t i_p dt.$$

If the discharge occurs at a constant current power, then

$$Q_p = I_p t_p,$$

where t_p – is the discharge time.

As the nominal capacity we assumed the capacity during a 10 hour discharge down to the 20.4 v at the batteries' terminals (with the initial electrolyte density of 1.285 g/cm^3 and a + 20°C temperature).

The capacity depends on a number of factors: the quantity and velocity of the active substance, thickness and area of the plates, temperature and density of the electrolyte, atmospheric pressure, discharge current value, and the preceding state of the battery.

A great effect on the capacity of the batteries is caused by the discharge conditions. As we can see from fig. 2.3, with an increase of the discharge current the capacity of the batteries drops sharply.

When the battery is discharge by currents which are greater than the rated currents, the capacity may be approximately be determined by the formula

$$Q_p = 0.4\, Q_{rat.} \lg \frac{I_{a\,max}}{I_p},$$

where $I_{a\,max}$ - is the short-circuit current of the battery;

I_p - is the discharge current of the battery with which we determine Q_p.

The value of the battery's capacity is affected considerably by the electrolyte temperature also. With the lowering of the temperatures the capacity drops.

The capacity of the battery at a low temperature is determined with the formula

$$Q_\nu = Q_{20}\,[1 + 0.01\,(\nu - 20°)],$$

where Q_ν - is the capacity at temperature ν;

Q_{20} - is the capacity at a temperature + 20°C.

$$\nu = \nu_\kappa + (\nu_H - \nu_\kappa)\, e^{-\frac{t}{T_{cont}}},$$

where ν_κ - is the temperature of the surrounding medium;

ν_H - is the initial temperature of the electrolyte;

T_{cont} - is the time constant of the battery with the container;

t - is the flight time.

In aircraft the batteries are installed in special containers which reduce the heat transfer and preserve from mechanical damage and penetration of oil, water, and other substances.

The containers are usually made of pure aluminum with a heat insulating, hazard resisting lining of deer-hair felt, hard Anozol plastic. The thickness of the heat-insulation layer usually does not exceed 15 - 20 mm. The temperature of the electrolyte should not be lower than -5°C. During prolonged flights under low temperature conditions, the heat insulation does not produce the desired effect, and the battery has to be heated.

The principal technical data for storage batteries are given in table 2.1.

The simplified diagram of the battery feeder and the airport power supply connectional roses, presented in fig. 2.4, assures the solution of the following problems:

1. Connection of batteries 101 and 102 to the aircraft's power system busbars 41A and 42B, by means of conductors 103 and 104 and switches 107 and 108. The latter is used during an emergency situation.

2. Prevention of connection of batteries to the power system aboard the aircraft, when there is an incorrect polarity. In this case the semi-conductor opens the relay 105 (106), the latter operates and the conductor's feed circuit 103 (104) is broken.

Table 2.1: Principal technical data of storage batteries.

1) Тип аккумулятора	2) Номинальное напряжение, в	3) Режим основного разряда: 4) время, час	5) ток разряда, а	6) емкость, а·час	7) конечное напряжение на элементе, в	8) Вес, кг	9) Относительный вес, кг/а·ч	10) Высота, км	11) Температура, °C
12-А-10	24	10	1,0	10	1,7	14,5	1,45	15	+50+—50
12-А-30	24	10	3,0	26	1,7	27,8	1,07	15	+50+—50
12-АО-50	24	10	4,8	48	1,7	54,0	1,12	15	+50+—50
12-САМ-28	24	5	5,6	28	1,7	28,5	1,02	17	+50+—50
12-САМ-55	24	5	11	55	1,7	55,0	1,00	18	+50÷—50
12) 15-СЦС-45	27	5	9	45	1,6	14,3	0,32	20	
12-АСАМ-23	24		5	21	1,8	30,0	1,42	35	+50+—50
13) 20-КБН-30	24	3	10	30	1,0	36,0	1,2	36	+50+—5

1. Battery type.
2. Rated voltage, v.
3. Basic charging conditions.
4. Time/hours.
5. Discharge current, amp.
6. Capacity amp/hours.
7. Final voltage at the cell, v.
8. Weight, kg.
9. Relative weight, kg/amp.hour.
10. Altitude, km.
11. Temperature, °C.
12. 15-SZS-45, and 13. 20-CNB-30.

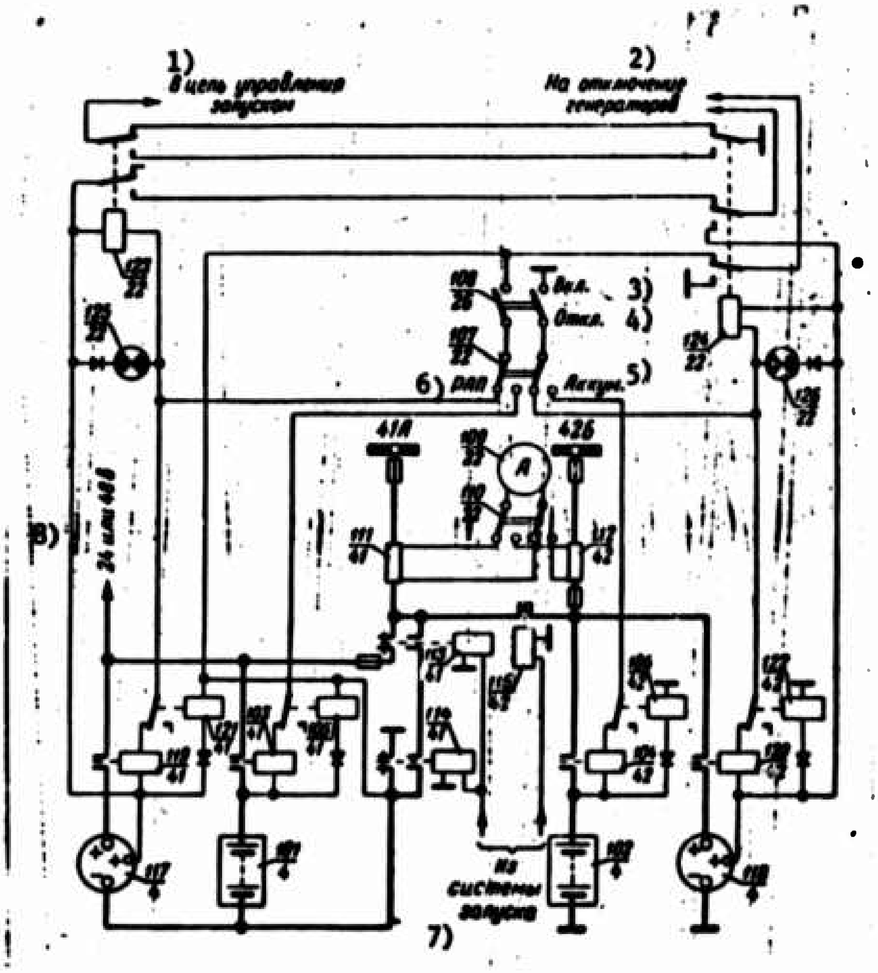

Fig. 2.4. Diagram of control and protection of battery feeders and airfield power supply connection roses.
Key: 1. Into the starting control circuit; 2. To switching off of the generators; 3. On; 4. Off; 5. Battery; 6. RAP; 7. From the starting system: 8. 24 or 48 v.

3. Consecutive control of battery current by means of amperemeter 109 and two-way switch 110.

4. Automatic switching over of the batteries by conductors 113, 114, and 115, on the signals of the starting system, with a voltage of 48 v, for supplying power to the electric starter. In this case the aircraft power system receives a voltage of 24 v.

5. Paragraphs 1, 2, 3, and 4, apply completely to the process of a switch-over to the aircraft power system of the airfield power supply connection roses 117 and 118. For this purpose the two-way switch 107 is set up in the "RAP" position.

6. The degrees of a possibility of a burning of the power conducts of the conduct-rose 117 (118) at the moment of connection of its ground part to the aircraft part. This is achieved by the greater lengths of power beams in connection with the control beams.

7. Automatic disconnection of aircraft generators from the power system by means of the 123 (124) and connection of the signal lamp 125 (126) when anyone of the connection roses is plugged in.

8. It excludes the possibility of a starting of the aircraft engine when only one airfield power supply connection rose is plugged in. This is performed through the consecutive passage of control circuit by starting through the normally disconnected contacts of relay 123 and 124.

If it is not required to switch over the system from 24 to 48 v, then conductors 113, 114, and 115 are not installed and the system is simplified accordingly.

2. Direct Current Generators.

Generators of the GS and GSRC with a capacity of 3 - 18 kw voltage of 28.5 v with forced cooling, have become widely used in aircraft. These generators are characterized by sufficient reliability, compactness, operation at high altitude (up to 20 km and more), speed (n = 3800 - 9000 rpm), small relative weight (3.7 - 2 kg/kw), and high efficiency (0.75 - 0.78).

The weight of a d-c 30 v generator is determined with the empirical formula [1]:

$$G = 14\left(\frac{R_{rated}}{n_{initial}}\right)^{0.67} \text{kg}.$$

From this formula we can see that the increase of the initial rate of revolutions $n_{initial}$ makes it possible to decrease sharply the weight of the generator or increase its rated capacity, and improve its operating characteristics. Thus, in generators operating at a constant rate of revolutions, the excitation power and dimensions of the equipment decrease substantially, under the voltage regulation precision, improves through the decrease of the range of excitation current variations.

The principal technical data of the d-c generators are given in table 2.2.

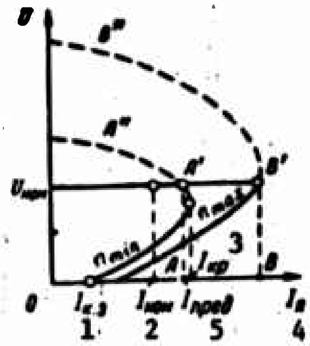

Fig. 2.5. External characteristic of a generator with parallel excitation, operating with a regular voltage.
Key: 1. $I_{short\text{-}circuit}$; 2. I_{rated}; 3. I_{max}; 4. $I_{armature}$.

The generator is determined by the external characteristic (fig. 2.5), which represents the dependence of the voltage at the generator's terminal, on the load currents, with the constant resistance in the excitation circuit and constant rate of rotation.

In a generator, operating without the voltage regulator (the characteristic is drawn in a broken line) upon an increase in the load, the voltage decreases because of the drop of voltage in the armature winding, and in the brush contact, the reaction of the armature, and decrease of the excitation current.

With an invariable resistance of the excitation circuit, with the increase of the rate of revolution, the external characteristic is located higher, while the critical current value (I_{cr}) increases.

The value of the stabilized short-circuit current (I_{sc}) is determined by the value of the magnetic flux of the residual magnetism and the rate of revolution, and is usually less than rated (I_{rated}).

Aviation generators operate with automatic voltage regulators. The voltage regulator, beginning with idling and up to the maximum load I_{max} (which is higher than rated), maintains the voltage practically unchanged.

The maximum current (overload capacity) which may be obtained from the generator under a rated voltage increases with the increase of the rate of revolution and reaches the highest value at the maximum velocity (sector OB).

The maximum and critical currents are selected for minimum permissible velocities of rotation and are assumed to be equal to

$$I_{max} \approx 1.8 I_{rated}; \quad I_{cr} = 2 I_{rated}.$$

They may be increased through use of compensational winding, which compensates the effect of the armature reaction.

3. Non-Conduct D-C Generators.

During supersonic flights and at altitudes higher than 18 km, it is difficult to cool the conventional generator mainly because of the presence of the collector and pressures. Inspite of a number of design measures undertaken, and the use of special materials, the collector-brush unit remains the least reliable element of the d-c generator under these flight conditions.

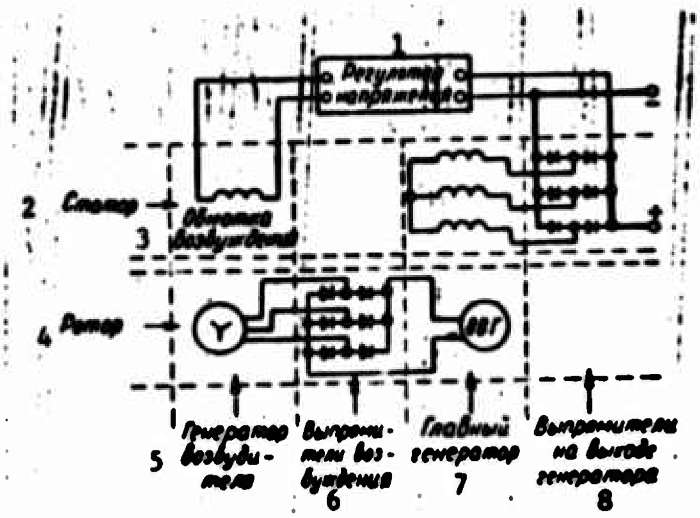

Fig. 2.6. Diagram of the non-conduct d-c generator. Key: 1. Voltage regulator, 2. Stator, 3. Excitation winding, 4. Rotor, 5. Generator of the exciter, 6. Excitation rectifiers, 7. Main generator, 8. Rectifiers at the generator's output.

With the development of the semi-conductor technology, powerful silicon diodes have appeared, which make it possible to create non-conduct d-c generators.

The non-conduct generator (fig. 2.6) includes 4 basic elements: d-c exciter, main generator excitation rectifiers, main generator, and rectifiers at the output of the main generator.

The output from the operating coils of the d-c exciter is delivered through the excitation rectifiers to the excitation winding of the main generator. All these elements were assembled on a rotating rotor, which excludes the necessity of the use of sliding contacts between them (collector and brushes).

The voltage from the operating coils from the main generators is delivered through the output rectifiers, from which the rectified current is delivered to the supply system and simultaneously through the voltage regulator to the voltage coils of the exciter. The above mentioned elements are located in the stator and require no sliding contacts for connection between one another.

The exciter is a high capacity amplifier and operates with an insignificant excitation current in comparison with the excitation of the main generator. This makes it possible to use for the exciter an automatic voltage regulator with small capacity, which results in a decrease of its dimensions, weight, and amount of remote heat.

The non-conduct direct current generators with static voltage regulators make it possible to use a d-c for various types of supersonic and high-altitude aircraft, if it is necessary for supplying the main consumers.

The weight of the generator per unit of power amounts to about 2 kg per kw.

Chapter 3. Voltage Regulation and Protection of Direct-Current Generators.

1. Voltage Regulator of D-C Generators.

The voltage of generators under all operating conditions, i. e., with a variable rate of revolution, and load variations from 0 to maximum ($I_{max} \approx 2I_{rated}$) should be maintained practically constant.

This task is carried out by automatic voltage regulators, which, while they change the resistance in the excitation circuit, act upon the value of the generator excitation current and in this way maintain their voltage constant and the load distribution regular during the parallel work of the generators.

For automatic voltage regulation of generators with excitation currents of more than 2 amp., carbon voltage regulators of the R, RUG,

Table 2.2:

1 Тип генератора	2 Номинальные данные 3 мощность $P^{o}_{ном}$, *квт*	 4 напряжение U, *в*	 5 сила тока I, *а*	 6 скорость n, *об/мин*·10^{3}	7 Вес G, *кг*	8 Относительный вес $G/P_{ном}$, *кг/квт*	9 Высотность H, *км*	10 Расход и давление воздуха, *дм³/сек*, *мм вод. ст.*	11 Габариты 12 диаметр, *мм*	 13 длина, *мм*
ГСР-3000	3,0	28,5	100	4,0—9,0	11,3	3,84	15	40/	146	245
ГСР-6000	6,0	28,5	200	4,0—9,0	20,9	3,48	18	70/260	166	348
ГСР-9000	9,0	28,5	300	4,0—9,0	24,0	2,67	15	95/260	166	306
ГСР-СТ-9000*	9,0	28,5	300	4,0—9,0	28,0	3,11	20	75/300	186	306
ГСР-12000	12,0	28,5	400	4,0—9,0	28,6	2,38	15	160/400		
ГСР-СТ-12000*	12,0	28,5	400	4,0—9,0	31,0	2,58	18	145/360	179	436
ГС-12	12,0	28,5	400	4,2—9,0	33,0	2,75	15	160/400	196	382
СТГ-12Б*	12,0	28,5	400	4,2—9,0	31,5	2,63	15	160/400	199	382
ГСР-18000	18,0	28,5	600	4,0—9,0	41,5	2,3	15	225/400	198	479
ГСР-СТ-18000*	18,0	28,5	600	4,0—9,0	43,0	2,39	15	225/400	198	427
ГС-18	18,0	28,5	600	4,2—9,0	40	2,22	15	160/400	205	448
СТГ-18*	18,0	28,5	600	4,2—9,0	46	2,55	15	180/400	205	496

1 Тип генератора	14 Число полюсов 15 основных	 16 дополнительных	17 Регулирующая аппаратура 18 минимальные реле	 19 регулятор напряжения	 20 точное регулирование напряжения	 21 защита от перенапряжения	 22 стабилизирующий трансформатор	 23 выносное сопротивление	 24 минусовое сопротивление
ГСР-3000			ДМР-400Д	Р-25АМ			ТС-9АМ	ВС-25Б	РС-7
ГСР-6000			ДМР-400Д	Р-25АМ			ТС-9АМ	ВС-25Б	БС-6000
ГСР-9000	6	3	ДМР-400Д	Р-25АМ РУГ-50	ДКН-2		ТС-9АМ	ВС-25Б	РС-2
ГСР-СТ-9000*			ДМР-400АМ	Р-27 РУГ-50	ДКН-2		ТС-9АМ	ВС-25Б	РС-2
ГСР-12000	8	4	ДМР-400Т	РУГ-50 Р-25АМ РУГ-82	ДКН-2		ТС-9АМ	ВС-25Б	БС-12000
ГСР-СТ-12000*			ДМР-400А	РУГ-82 РУГ-83	ДКН-2		ТС-9АМ-12	ВС-20Б	БС-12000
ГС-12			ДМР-400Т	РН-180					БС-12000
СТГ-12Б*	6	6	ДМР-400Т	РН-180Б РНК-180Б	ЦКН-8Д	АЗП-Ц		ВС-20	БС-12000
ГСР-18000	8	4	ДМР-600Т	РУГ-82 РУГ-83	ДКН-2		ТС-9М		БС-18000
ГСР-СТ-18000*			ДМР-600Т	РУГ-82 РУГ-83	ДКН-2		ТС-9АМ	ВС-20	БС-18000
ГС-18	6		ДМР-600Т	РНК-180Б	ЦКН-8Д	АЗП-Ц		ВС-20	
СТГ-18*	6		ДМР-600Т						

1. Generator type.
2. Rated data.
3. Power, P**, of rated kw.
4. Voltage, U, v.
5. Current power, I, amp.
6. Speed, n, rpm/times 10^3.
7. Weight, G, kg.
8. Relative weight, G/P_{rated}, kg/kw.
9. Altitude, H, kw.
10. Flow rate and air-pressure, dm^3/sec/mm water column.
11. Size
12. Diamter, mm.
13. Length, mm.
14. Number of poles.
15. Main.
16. Auxiliary.
17. Regulating equipment.
18. Minimal relays.
19. Voltage regulator.
20. Precision voltage regulation.
21. Protection against over-voltage.
22. Stabilizing transformer.
23. Remote resistance.
24. Minus resistance.
25. *), starter-generator.
26. **), capacity is given with U =30 v.

and RN series are used, which change smoothly the resistance in the excitation circuit.

These regulators have the same design diagram (fig. 3.1) and differ with respect to its details, structure of individual units, certain elements of the electrical circuit, and the parameter values.

The regulator has two main elements: the carbon column 1 and electric magnet, consisting of a core 2, main winding W_e and a levelling winding W_y. The carbon column consists of a set of thin carbon washers, placed on a ceramic pipe 3, which is fixed on a ribbed body 4. On both sides of the carbon column are carbon contacts 5 insulated from the body, installed on holders 7. The latter transmit the pressure to the carbon column and connect it with the excitation winding W_b of the generator. The pressure on the carbon column depends on the action of the mechanical spring 9 and the electric magnet. By means of a regulating screw 8, we can change the pressure of spring 9 on the carbon coulmn, changing in this way the tune-up of the regulator. The core 2 is threaded, which makes it possible to regulate the air-gap x of the electric magnet. The attraction of armature 6 to the core 2 is opposed by spring 9 on which the armature is rigidly fixed.

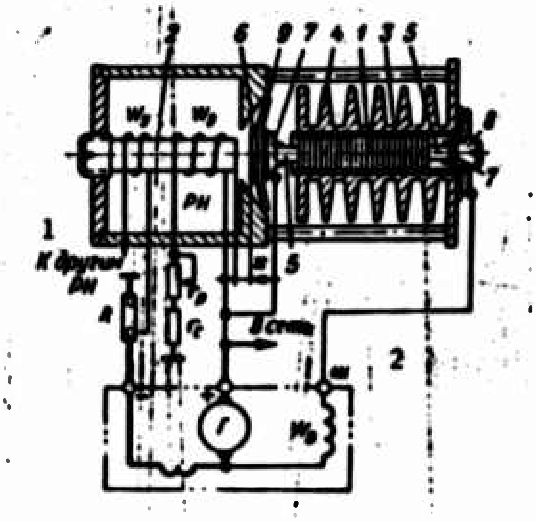

Fig. 3.1. Structural diagram of a carbon voltage regulator: 1 - carbon column; 2 - core; 3 - ceramic tubes; 4 - ribbed body; 5.- carbon contacts; 6 - armature; 7 - holder; 8 - regulating screws; 9 - spring. Key: 1. to other R_n, 2. into the power system.

The regulator also has temperature compensation facilities: special resistances and windings for precision voltage maintenance under different temperature conditions and stabilization facilities for assuring a stable work of the regulator under transient conditions. In the work of the regulator the pressure on the carbon column may be changed by means of the electric magnet, the winding W_e of which is connected to the generator terminals by means of the regulated resistance R_b.

Upon the increase of the generator voltage the current in the winding W_e increases, the pressure on the column decreases, the resistance increases proportionally, the excitation current decreases, and this limits the voltage increase. Upon the decrease of the voltage, the regulation process occurs in the inverse order.

Regulator Tune-Up. Depending on the character and the mutual position of the electro-magnetic and mechanical characteristics of the carbon regulator, the voltage regulator may be static or astatic. In fig. 3.2 we show three possible cases of voltage tune-up.

Case A. The slope of the electro-magnetic characteristics F_{em} is smaller than the slope of the mechanical characteristic F_m. In the equilibrium position, corresponding to the intersection of the electro-magnetic and mechanical characteristics (point 1) with a gap $x = x_1$, the voltage regulated is equal to U_2. Upon the disruption of the equilibrium, for example as the result of a load-drop, the voltage increases and the operating point falls onto the electro-magnetic characteristics, corresponding to voltage U_4 (point 2). As a result of the voltage increase, the regulator goes into action, the air-gap x decreases, and the operating point moves to the left, until it again falls onto the mechanical characteristic f_m (point 3). A new equilibrium position corresponds to its voltage U_3 which is greater than the voltage U_2. In the case examined, the regulator is tuned up in such a way, that the load increase results in an increase in the voltage, and conversely, that is, the characteristic will be dropping with the load. This tune-up, which is used most extensively in aircraft regulators, is called the tune-up with the positive statics.

Case B. If the slope of the electro-magnetic characteristic is greater than the slope of the mechanical characteristic, then with the decrease of the load the voltage regulator decreases $U_1 < U_2$ (point 4). This is a tune-up with negative statistics.

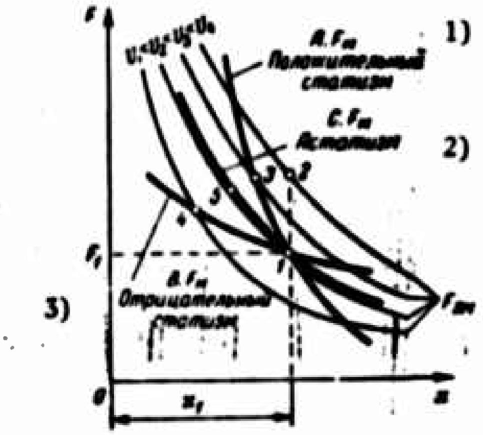

Fig. 3.2. Electro-magnetic and mechanical characteristics of a regulator with various types of tune-ups. Key: 1. $A.F_m$ - positive statics; 2. $C.F_m$ - half statics; 3. $B.F_m$ - negative statics.

Case C. If we assure the precise coordination in the working range of the characteristics of the electro-magnetic pole and mechanical characteristic, equal to the difference in the forces of the spring and the elastic deformation of the carbon column, then at the end of the regulating process, the operating point will be located on the initial characteristic, having moved from point 1 into point 5, which corresponds to the state of equilibrium under the new operating conditions. This tune-up of the voltage regulator is called astatic.

The precise core-incidence of the electro-magnetic and mechanical characteristics is usually difficult to obtain, therefore, all regulators have statism, which is determined by the selection of the operating point on the regulating characteristic (fig. 3.3). The operating point is selected during idling and the average rate of the rotation of the generator by compressing the carbon column through unscrewing the regulating screw. At point A, the carbon column is decompressed, the excitation current $I_b = 0$, and the voltage is created by the generator through residual magnetism. At the AB sector, the space between the carbon column washers is eliminated and the voltage almost does not increase at all. At sector BC the voltage increases rapidly through the compression of the carbon column washers, however, the compression forces are small and do not affect the position of the spring. The magnetic gap is great, and the electromagnetic forces are small. At the CD sector, the spring is weakly compressed and its mechanical characteristic is located below the electromagnetic force characteristic. Consequently, with the growth of the load the regulator may have a negative statism.

When the regulating screw is screwed out the compression of the carbon column increases the magnetic gap decreases and as a result so does the regulated voltage. Beyond point C' the regulator usually becomes unstable, since the spring begins to vibrate, causing a sharp voltage oscillation in the generator. This is explained by the fact, that the spring is first little compressed, and during any disruption of equilibrium (load-drop and others) the electro-magnetic force may compress the spring so far, that there is a break in the carbon column. In this case the excitation current, the voltage, and the electromagnetic force drop to 0, whereupon the column is compressed by the spring, and the voltage grows in the process of "popping", which is repeated. The "popping" condition is very dangerous for the regulator and therefore when the regulating screw is screwed out, this zone C'D' should pass rapidly.

Upon further movement of the screw at point D, the vibrations of the spring cease and the regulator becomes stable. Sector DE corresponds to the stable work of the regulator.

At point D the mechanical and electro-magnetic characteristics coincide. At this point the regulator is tuned-up astatically and with measurements of I and n the voltage regulated is not changed.

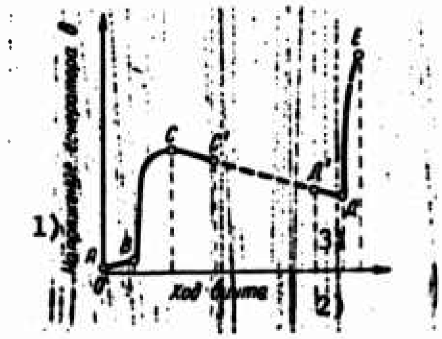

Fig. 3.3. The regulator's regulating characteristic. Key: 1. Generator voltage, v; 2. Screw pitch, 3. D.

At sector DE the spring is strongly compressed and its mechanical characteristics are above the characteristics of the electro-magnetic force. Consequently, with the growth of the load, the regulator has positive statics of voltage regulation.

When the regulating screw is screwed out, the rigidity of the spring increases, the mechanical characteristic ascends, and the regulated voltage increases.

The voltage level of the regulators changes by the screwing in or out of the electro-magnetic core. When the core is screwed in, the voltage drops, due to the decrease of the required, initial velocity, necessary for the creation of the same electro-magnetic pole and conversely.

2. The System of Precise Voltage Regulation and Protection against Over-Voltage.

The system consists of combined voltage regulators, central voltage corrector, and automatic device for protection against emergency voltage increase, and assures solution of the following problems:

1. Maintaining a voltage with an accuracy of $\pm$ 0.5 v, with a variation rate of revolution within the range of 4000 - 9000 rpm, and load from 0 to the rated load;

2. Uniform load distribution between generators working in parallel with a precision of $\pm$ (5-10)%;

3. Possibility of sub-regulating the load distribution by means of external resistances of voltage regulators;

4. Possibility of changing the voltage level of the power system aboard the aircraft by $\pm$ 0.75 v, by means of the regulating resistance of the corrector;

5. Manual switch-over from one corrector to another, if installation of a duplicating corrector is provided;

6. Operation of the protective automatic device under all emergency conditions, if the voltage at the collection busbars exceeds 34 v, and in this case the signal "over-voltage" lamp is lit;

7. During a sudden rise of voltage at the collection busbars the operating time of the protective device at 34 v is not greater than 1 - 3.5 seconds; and with 60 v it is not less than 0.04 - 0.1 second.

Let us examine some systems which we can select for the solution of the above mentioned problems.

System CVR is presented in fig. 3.4.

The regulator operates in the following manner. Upon the increase of the voltage the generator increases the current in the winding W_e, the action of the electric magnet increases, the pressure on the carbon column decreases, and its resistance increases, decreasing the excitation current of the generator and reducing its voltage accordingly.

The temperature compensation winding W_t is connected in parallel to the operating coil, the magnetizing power of the former being subtracted from the magnetizing power of coil W_e. The regulator is acted upon by the difference of these magnetizing forces. Windings W_e and W_t and the resistance of the temperature compensation R, are selected in such a way, that the increase of the magnetizing forces upon the change of the temperature of both windings, is approximately equal.

The stability of the regulator's work is achieved by introduction of a feed-bag by means of resistances and winding W_{st}.

When switch B_1 is closed, relay R_2 operates and turns on the equalizing winding W_y of the regulator to the common equalizing busbar, for all the generators operating in parallel. The value and direction of current in W_y depends on the difference in the regulating busbar potentials, and the minus brush of the generator, with which that regulator works. The equalizing current, passing through winding W_y, affects the regulator, raising the voltage of the under-loaded and reducing the voltage of the over-loaded generator.

The corrected winding W_k, by means of relay R_2, is turned on in parallel with analogous windings of the rigged voltage regulators, of the other generators, and receives the signals from the central voltage corrector (CVC).

The CVC system, a simplified central voltage control system, is presented in fig. 3.5.

The sensitive element of the CVC is a bridge, one of the arms of which contains a silicon stabilitron ST. The coils of the polarized relay R are connected to the diagonal of the bridge. Under rated voltage of the power supply system aboard the aircraft, the armature of the relay occupies the neutral position.

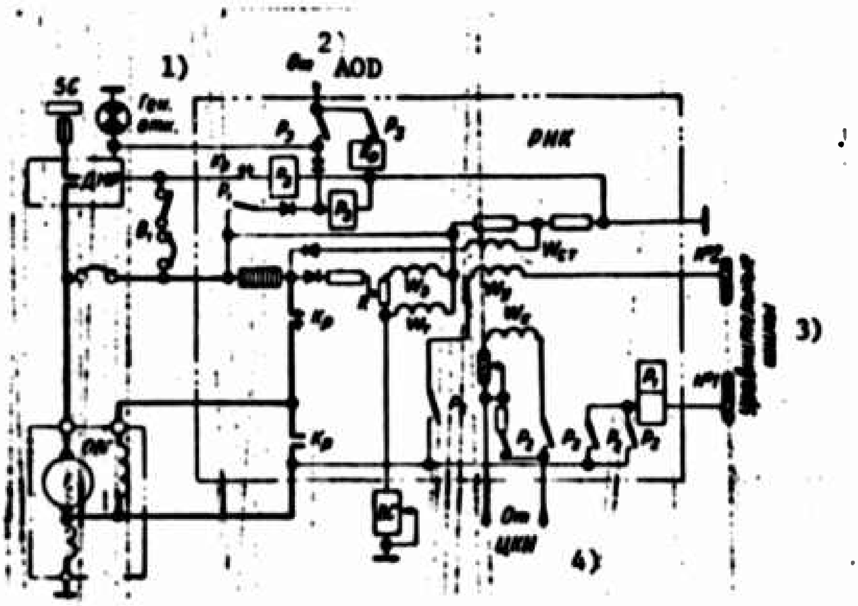

Fig.3.4. System of a combined voltage regulator (CVR): W_e - operating coil; W_y - parallel operation coil; W_k - correcting coil; W_{st} - stabilizing coil; W_t - temperature compensation.
Key: 1. Generator turned off; 2. from the automatic over voltage protection device (aod); 3. equalizing busbars; 4. from the CVC.

Upon the decrease of the voltage at the collection busbars, the armature passes into position L and capacitor C is charged. The great potential of tube L increases, the anodic current grows, the base potential and triode T resistance decreases, which results in a mismatch at the output bridge, consisting of R_6, R_7, R_8, and T, and consequently to the increase of current in the correcting coil W_k of the regulator.Winding W_k is connected in counter-current with W_e; the summation ampere-loops decrease, and the voltage at the buebar increases. As soon as the voltage reaches the rated value, the armature passes to the neutral position and remains there.

Upon the increase of the voltage at the collecting busbars, the armature passes into position B, condensor C begins to charge through resistor R_5. In this case the great potential and anodic current of the tube will decrease, the triode base potential will increase, the current in W_k and the voltage at the busbars will decrease. When the voltage reaches the rated value, the armature passes into the neutral position. In this way, the CVC operates as the vibration voltage regulator, the vibration frequency of the conducts being determined by the capacity of capacitor C and resistors R_4 and R_5. The voltage corrector circuit may be tuned-up in such a way that upon passage of the voltage generator through the rated value, the sign of the current in the correcting winding would change.

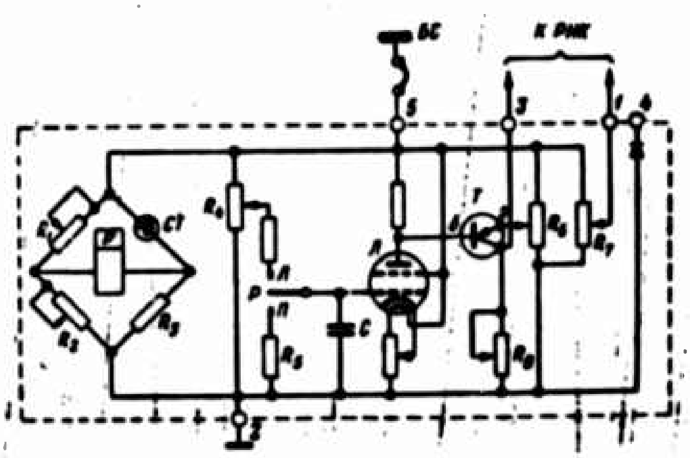

Fig. 3.5. The central voltage correction (CVC) diagram.

The CVC is an astatic regulator, since the armature may occupy a neutral position under any current in the correcting windings.

Usually, the sensitive part of the CVC are terminals 5 and 2, which are connected to such a point in the electric system, the voltage in which should be maintained constant, while the output terminals 1 and 3 are connected with the correcting windings W_k of the voltage regulators.

The AOD diagram is shown in fig. 3.6. The system of the power line protection from emergency voltage increase, consists of a central automatic protection device aod and a number of elements, included in each voltage regulator. The protective automatic device measures the general voltage level at the collection busbars, while the protective elements produce the selectivity.

The AOD has two identical sensors, two bridge circuits, the diagonal of which includes polarized relays R_{10} and R_{11}. The bridge circuits have a different tune-up: relay R_{10} operates under a voltage of 30 - 31 v, while relay R_{11} operates under a voltage of more than 33 - 34 v.

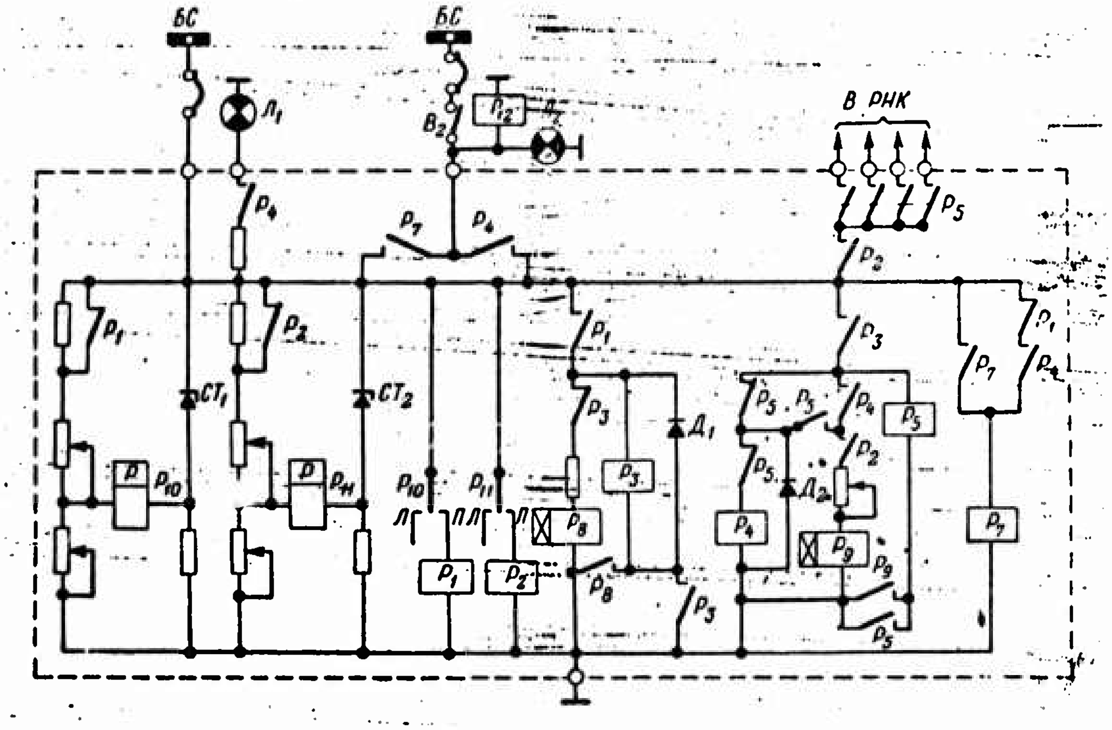

Fig. 3.6. Diagram of the automatic over-voltage protection device (AOD).

When relay R_{10} operates, relay R_1 is turned on, and after a certain time R_8; then R_3 is turned on which breaks the feed circuit of R_8, and blocks itself and turns on R_4. Relay R_4 turns on signal lamps L_1 and L_2, and switches over the system to the duplicating CVC, by means of relay R_{12}.

If the voltage has dropped to the rated voltage, relays R_{10}, R_1, R_3 and R_4 will be released. In this case relays R_3 and R_4 have a time lag, using diodes D in order to permit relay R_7 to operate, which locks itself and blocks relay R_{12}. If the voltage did not decrease, then it is necessary to determine according to the instruments the generator which is out of order, and to disconnect it.

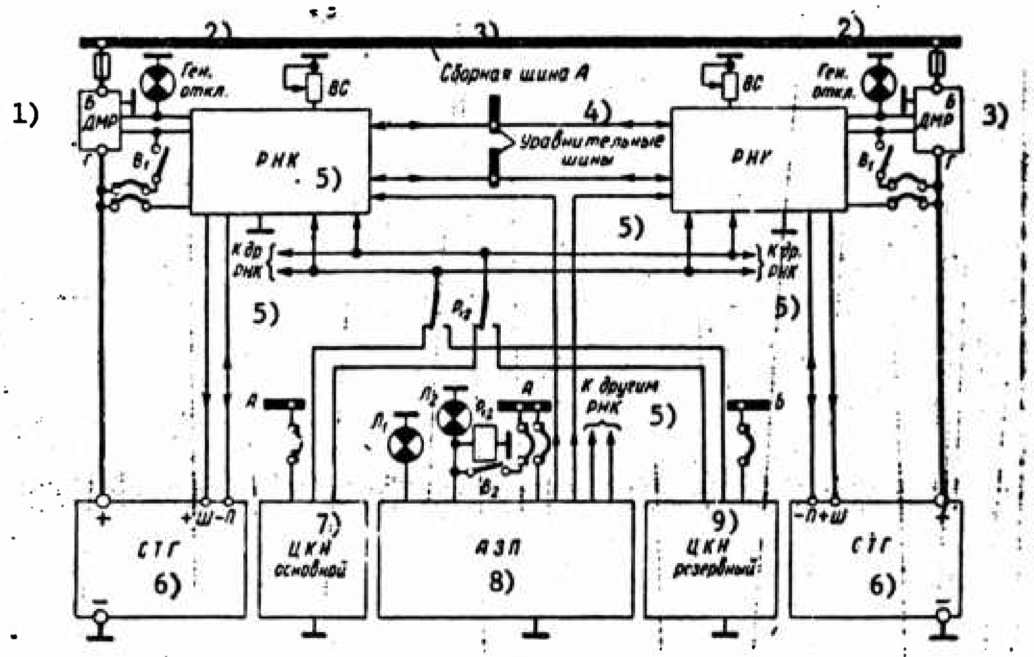

Fig. 3.7. Diagram of the external connections of the precise regulation and over-voltage protection system equipment.
Key: 1. DMR, differential minimum relay; 2. disconnected generator; 3. collection busbar A; 4. equalizing busbars; 5. to other voltage regulators; 6. starter generator; 7. main CVC over-voltage protection automatic device; 8. AOD; 9. reserve CVC. – 5' and 5" – VRC, voltage regulation corrector.

If the voltage has risen above 33 - 34 v, both relays R_{10} and R_{11} will operate. Relay R_{10} will perform the operations described above, and relay R_{11} will turn on R_2, which turns on the delayed action relay R_9. Since relay R_4 switches over the correctors, then when the main corrector is out of order, the voltage is restored, relay R_9 has not enough time to operate, and the circuit will return to the initial condition, having blocked the switch-over circuit of the correctors.

If after switching over of the correctors, the voltage will not decrease, the relays R_9, R_5 will operate. Relay R_5 breaks the feed circuit of R_4, and the system again switches over to the main corrector.

Relay R_5 sends signals to the VRC. R_1 of the generator out of order will not operate, and the signal falls on to the windings of conductor K_p (see fig. 3.4) which turns off the feed of the excitation circuit and closes it, in order to exclude the possibility of over-magnetizing of the generators.

At the generator in good working order by the moment at the arrival of the signal from the AOD, the polarized relay R_1 has enough time to operate and turn on relay R_3, which breaks the feed circuit K_p and excludes the possibility of its operation and disconnection of excitation of the generator in good working order.

In fig. 3.7 we give a diagram of the external connection of the equipment in the precise regulation and over-voltage protection system, the work of which has been examined earlier.

3. Protection of D-C Generators and their Feeders.

In order to preserve the working capacity of a power system when the generator or its feeder is damaged, a protection against over-voltages is provided for (it is has been examined earlier), as well as protection against loss of excitation, over-magnetization, overloads, and short-circuits.

This protection is given by the differential minimum-relay (DMR) which simultaneously serves for the automagnetic switching on and off of the generators under normal conditions.

There are different types of DMR for 200, 400, 600 and 800 ampere currents. All of them have the same purpose and simplified diagram (fig. 3.8) and differ only with respect to the auxiliary elements and power conductors.

The DMR fulfills the following functions:

- it connects the generator to the power line, if its voltage is not lower than 14 - 19 v and exceeds the power system voltage by 0.2-1 v;

- it disconnects the generator from the system upon a reverse current (15-35 A for the DMR-400, and 25-50 A for DMR-600), which originates upon the loss of excitation by the generator or short-circuit at the DMR-generator sector;
- it does not connect the generators to the power line with an incorrect polarity, which includes the possibility of its overmagnetization;
- it gives out signals on disconnection of the generators or break in the feeder line at the sector between the generator and the DMR;
- it provides non-automatic (manual) connection of the generator to the system.

The DMR consists of the differential relay D_r contactor K, connection relay R_c, protection relay R_p, forcing relay R_f, and relay for switching the coils of the differential relay, and signalling R_s.

A command element is the differential relay. It has two coils, the one in series, SO (one loop), over which passes the generators' current, and the differential GEO, connected to the difference of the voltages between the generator and the system.

The magnetic system of the differential relays (see fig. 3.8), consists of steel plates 1 and 2, permanent magnets 3, and poles 4 and 5. The steel armature 7, passes freely inside the SO and DO coils, is fixed on bracket 6, and can turn by a small angle for touching contacts screw 8, or supporting screw 9.

Depending on the direction of the total ampere-loops of the coils, the relay armature is magnetized in a certain direction and its ends are drawn to the fixed poles of the opposite polarity. The relay has no counter-acting spring, therefore, when the coils lose the current, the armature occupies the position which it occupied before the windings were turned off.

When the switch B is turned off, the winding of relay R_c is connected to the generator. When the voltage of the generators gradually increases as the engines turn more rapidly, reaches 14 v, the relay operates.

When contancts 1-2 of R_v close, winding of R_z and the shunt winding of differential relay D_r are connected to the potential difference between the generator and on-board power system.

If at the moment of connection of relay R_c the above mentioned voltage difference reaches value 12-16 v, relay R_p operates, and having opened the contacts, preserves the winding of D_r from prolonged stay under current, since the winding of D_r is calculated for a long work under a voltage of not more than 15 v. Relay R_p also excludes the possibility of connection of the generator to the power system with incorrect polarity.

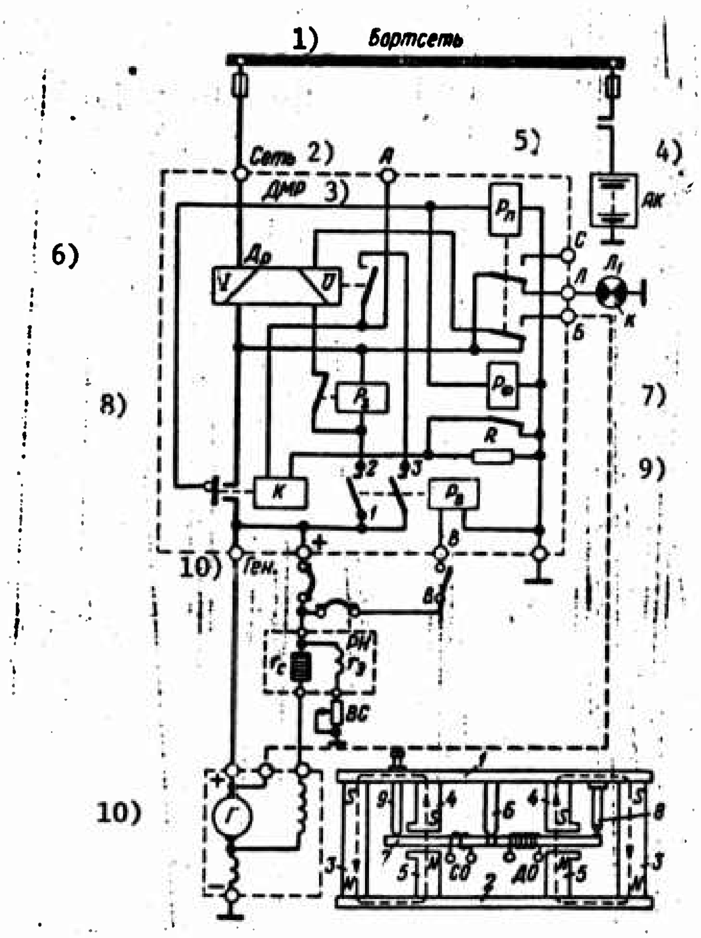

Fig. 3.8. Block electrical circuit diagram of the generator with the DMR protection system.
Key: 1. power supply system aboard the aircraft; 2. power supply system; 3. DMR; 4. storage battery; 5. R_{ε}; 6. D_r; 7. R_f; 8. R_p; 9. R_c; 10. generator.

With the increase of the voltage on the generator, the voltage difference of the generator and the power system aboard the aircraft decreases, and when it reaches 3 - 5 v, the relay operates for release, the contacts will close and D_r winding will again be connected to the voltage difference.

If the D_r contacts at the moment of connection of its winding were closed, the magnetic field created by the coils will be of the same direction as the one during which the contacts will be open; if they had been opened, then they will be held by the magnetic field int the open space.

When the voltage of the generator exceeds the voltage of the power system aboard the aircraft by 0.2 - 1 v, the magnetic field of D_r will change its direction and will move the small armature into position during which the contacts D_r will be closed.

In this case, the winding of conductor K through contacts 1 - 3 of relay R_c, contacts of D_r and contacts of relay R_f will be connected to the generator voltage; the conductor will operate and will connect the generator into the system through its power contacts.

When the contacts are closed the voltage is delivered to the coils of relay R_f, which will operate, open its conducts, and connect in series with the conductor winding, the additional resistance R, which decreases the current of the conductor's winding, preserving it from over-heating.

Relay R_f has a relatively high disconnection voltage value (8-12 v) which results during deep voltage dips in its release, shortening of resistance R, and increase of the conductor coil current.

Simultaneously with relay R_f relay R_s operates, switching over the end of D_r winding from the "system" terminal to the generator feeder line, breaks the circuit of the "generator disconnected" lamp and closes the consumer protection circuit.

If the voltage at the generator will decrease and become lower than the voltage in the system, the current in the series coil will change its direction. The magnetic field of D_r will correspondingly decrease its direction and will throw over the armature into the other extreme position, during which the contacts of D_r will open. In this case, the conductor will disconnect the generator, relay R_f, and relay R_s from the power line, and the system will be in the "generator disconnected" position. The winding of D_r will switch over from the generator to the "power line" and resistance R will be shunted. Relay R_p will operate and break the circuit of the D_r coil.

If the voltage of the generator will decrease further and become smaller than 5 v, then relay R_c will operate to disconnect and will open the circuit of relay R_p coil, its contact will close, but this is not dangerous for winding of D_r, since its circuit is now broken by contacts 1 and 2 of relay R_c, the DMR goes into the initial position, to connect the generator to the power line,if its voltage will rise again.

When the feeder line is broken, the current will not flow over the series winding, and on the shunt winding a current will flow in such a direction, that the armature will be thrown into the conduct-opening position. The conductor is disconnected, and removes the current from the coils of relay R_s.

The DMR may be used for connecting the generator as a starter when the aviation engine is started. In this case the current is delivered to the terminal A from an outside source.

The protective system of the generator in its feeder line during short-circuits should satisfy the following conditions:

1. The short-circuit in a feeder line inside the generator should not result in damage to the generator itself and to putting it out of order in the power system.
2. The protective system should disconnect the damaged generator from the power line and extinguish its excitation field, breaking the excitation winding and shorting the winding of the auxiliary poles.
3. The damage to the protective system should not result in a false disconnection of the generator from the power system.

D-C generators are not equipped with a special protective device against short-circuits, its role is partially carried out by the DMR and the maximum-current fuses.

<u>The following takes place during a short circuit</u>.

At the <u>"generator-DMR" sector or in the generator itself</u>:

1. The DMR disconnects reliably the short-circuit point from the external system if the reverse current does not exceed the breaking capacity of the DMR.
2. The generator's cut-out does not operate because of the short time of passage of the current in the generator, supplies power to the short-circuit point.
3. In the presence of three and more generators in a system, the breaking capacity of the DMR may prove insufficient to disconnect the system from the damaged feeder line. The DMR conducts are welded together. In this case the generator cut-out operates and disconnects the short-circuit point from the external system, but the fire hazard is not decreased.

At the <u>"cut-out - DMR" sector</u>:

1. The cut-out operates if the energy of the external network sources is sufficient. The external system is disconnected from the short-circuit point.
2. The generator operates at the short-circuit point, since the short-circuit current for the DMR is direct.
3. The considerable voltage drop (up to 1 - 4 v) on the DMR conductor coil, brings about the "ringing" conditions and may result in welding together the DMR conducts. A stable short-circuit regime originates for the generator, which is the most dangerous, because it puts out of action the DMR and the generator.

At the generator busbar:

1. All the energy sources operate for the short-circuit point.
2. A deep voltage drop (up to 1-4 v) all the DMR enter the "ringing" conditions, their conducts may be welded together.
3. With certain lay-outs of the feed system, the selective protective system may disconnect the damaged busbar from the power system.

The control and measuring equipment circuits have a length exceeding by several times the length of the power circuit, therefore in these circuits, protective automatic devices are installed also.

Protection of generators against over-loads. The length of the work of a generator during over-loads depends on the value of the current and thermal properties of the generator. According to the norms, the generators should hold up under a current over-load of 1.5 I_{rated} during 5 min., and $2I_{rated}$ during 5 seconds.

The system protecting the generators from over-loads should react to heating of the most vulnerable parts of the generator and reduce the current of its load in relation to the heating conditions to such a value, with which the heating temperature does not exceed the permissible limit. For this purpose a thermal relay is built into the generator. The flight conditions determine the necessity of removing the load or disconnecting the generator.

The use of the maximum current relay does not assure the protection of the generator from over-heating, since it limits only the current value, and not the length of its action. Moreover, on an aircraft with large capacity consumers, the batteries are unable to cover the peak loads, therefore, the load current of the generators cannot be limited and their capacities should be selected ahead, taking into account the peak loads.

To protect the generators from currents during short-circuits, high-melting fuses of the TP type have become widely used, which are calculated for disconnecting the generators only during prolonged overloads.

Chapter 4: Parallel Work of Direct Current Energy Sources.

1. Specific Features of the Parallel Work of D-C Generators.

The continuous growth of capacity of the consumers is accompanied by the increase of the number and power of the generators, so that it has become necessary, that they would work in parallel.

The parallel work of the generators in comparison with separate work has a number of advantages:

1. The reliability of electric power supply increases, because when part of the generators go out of commission, the uninterrupted power supply to the most important consumers continues.

2. The required power reserve of the energy sources decreases from 100% to 50% and below, which makes it possible to decrease the flight weight while the high reliability of the electric power supply remains.

3. The starting and power supply to electric motors which exceed the capacity of any single generator, is provided for, without decreasing the quality of electric power supply to other consumers.

4. It becomes possible to install batteries of lower capacity.

With the parallel work of the generators it is necessary to carry out the following conditions:

1. The generator voltages should be equal.

2. The polarity of the generators connected to the common busbars, should be the same.

3. The parallel work should be stable, with a substantial power difference of the generator in the aircraft engine (the power of the generator amounts to 0.5 - 2%).

4. The uniform distribution of the load between generators of a similar capacity working in parallel with different variations of rpm. This is attained by fulfilling additional conditions, which are examined below.

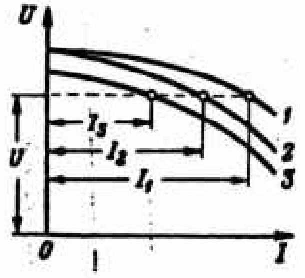

Fig. 4.1. Distribution of loads between generators working in parallel with natural external characteristics.

If generators of the same type and equal capacity have identical external characteristics and rpm, then with parallel work they will yield equal currents to the load. However, with different external characteristics, or rpm, the loads are distributed irregularly.

In fig. 4.1 we present natural external characteristics of the generators. From the characteristics of generators 1 and 2 we can see that with equal rpm and loads, generator 2 which has a steeper external characteristic yields a smaller current to the power system.

If generators 2 and 3 have identical external characteristics, but different rpm, $n_2 > n_3$, then generator 2 will yield to the power system a larger current than generator 3.

In the cases examined, the change in the rpm or size of the load is accompanied by fluctuations of the generators' voltage.

In this way, with different external characteristics and rpm, the parallel work of generators is practically impossible without voltage regulators with additional elements for parallel work.

With non-uniform load distribution between the generators, the permissible capacity of the power system is eliminated by the generator carrying the greatest load.

For a more uniform utilization of the capacity available, it is necessary to distribute the load uniformly between them, which is attained by means of voltage regulators.

The parallel work of generators is considered satisfactory, if under all operating conditions the load is distributed uniformly with a precision of ± 10%, while the voltage of the power system at the point where the voltage regulator is connected, is maintained constant within the limits of close to ± 2% of the rated voltage.

2. The Place of Voltage Regulator Connections.

In fig. 4.2 we show three variations of connections of voltage regulations: 1 - to the common busbars, 2 - to the generators' terminals, and 3 - to the terminals of the DMR. The place where the operating coil of the regulator is connected, has a substantial effect on the polarity of load distribution during parallel work of the generators.

When the regulators are connected to the common busbars, the following expressions are correct:

$$I = I_1 + I_2;$$

$$\frac{U}{R} = \frac{U_1 - U}{R_1} + \frac{U_2 - U}{R_2};$$

$$\frac{U_1}{R_1} + \frac{U_2}{R_2} = U\left(\frac{1}{R} + \frac{1}{R_1} + \frac{1}{R_2}\right).$$

where I - is the total load current;

I_1 and I_2 - are currents of the generator;

U - is the voltage on the common busbars;

U_1 and U_2 - are voltages of the generators' terminals;

R - is the load circuit resistance;

R_1 and R_2 - are resistances of this circuit, connecting the plus terminals of the generators with the busbars.

With this circuit diagram each regulator reacts to any voltage deviation on the busbar and strives to maintain it constant. When the load resistance is unchanged,from the last expression we obtain

$$U_1R_2 + U_2R_1 = \text{const.}$$

This equation is correct with an infinite quantity of voltage values U_1 and U_2, that is, the arbitrary load distribution is possible between generators operating in parallel. For a uniform distribution of the load between generators with $R_1 = R_2$ the voltages at their terminals should be equal, i. e., $U_1 = U_2$.

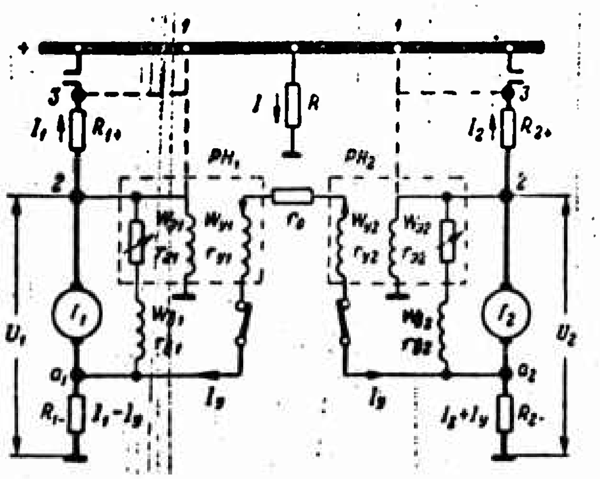

Fig. 4.2. Simplified circuit diagram of the parallel work of two generators with angle voltage regulators.

When the regulators are connected to the generator terminals, we can write:

$$U_1 = U + I_1 \cdot R_1 ;$$

$$U_2 = U + I_2 \cdot R_2 ;$$

$$\frac{I_1}{I_2} = \frac{U_1 - U}{U_2 - U} \cdot \frac{R_2}{R_1} ;$$

from which after transformation we obtain

$$\frac{I_1}{I_2} = \frac{(U_1 - U_2) + IR_2}{(U_2 - U_1) + IR_1}$$

In this case the regulators strive to maintain constant U_1 and U_2. Consequently, with an unchanged load current I and constant values of R_1 and R_2 the load may be distributed single-valuately. For a uniform load distribution between generators with all values of I, it is necessary that $R_1 = R_2$ and $U_1 = U_2$.

Usually in real power systems, the operating coils of the voltage regulators are connected directly to the DMR terminal. This makes it possible to raise the voltage stability at the distribution busbars, and in combination with the equalizing winding, to obtain practically uniform load distribution between the generators.

The equalizing winding used in regulators is intended for automatic equalizing of generator voltage for a uniform load distribution between them. It has a small number of coils and is located on the same electro-magnetic core of the regulator as its operating coils.

When the generators work with angle voltage regulators, the equalizing coils are connected between the negative terminals of the generators, as it is shown in fig. 4.2.

The current in the equalizing circuit is created through the difference of the potentials, arising because of the unequal voltage drop at the calibrated ballast resistances R_-, connected into the minus circuits of the generators.

If $U_1 > U_2$, a $R_{1+} = R_{2+}$; $R_{1-} = R_{2-}$, TO $I_1 > I_2$

Consequently, the voltage drop at the balanced resistance R_{1-}, is greater than at R_{2-}, and the potential at point a_2 will be higher than the potential at point a_1, as a result of which the equalizing current will flow from a_2 to a_1.

The magneto-motive forces of the equalizing and operating coils of the regulator RN_1 add up. As a result of this the attractive force of the electro magnet increases, the angle column lengthens, its resistance and consequently the excitation circuit resistance increases, which results in a decrease of U_1.

The magneto-motive forces of the equalizing and operating coils of regulator RN_2 are subtracted from one another, which results in an increase of U_2.

In this way, the currents passing through the equalizing coils, tend to reduce to a minimum the imbalance of the voltage $\Delta U = U_1 - U_2$.

In order to increase the effectiveness of the action of equalizing coils, their resistance and that of the connecting conductors should be minimum, which increases the ampere coils with small values of ΔU.

3. Parallel Work of Two Generators of Equal Power.

With any value of the external load its distribution between parallelly operating generators of equal power (fig. 4.2) should be uniform for all operating conditions, and this is possible only if five conditions are fulfilled:

1. Coincidence of voltage regulator characteristics of generators working in parallel within the limits of the entire range of rpm variations. $U = f(n) = \text{const.}$, i. e., astatic regulators;
2. The equality of regulators tune-up voltages during idling; $U_{10} = U_{20}$;
3. Equality of resistances of the plus sectors of generator circuits: $R_{1+} = R_{2+}$;
4. Equality of the resistances of the minus sectors of generator circuits: $R_{1-} = R_{2-}$;
5. Equality of resistances of the corresponding equalizing coils and equalizing conductors: $r_1 = r_2$.

It is practically impossible to fulfill all these conditions, because there is always a non-coincidence of the characteristics, detuning of voltage regulators, and an unequality of conductors' resistance in the plus, minus, and equalizing circuits.

The total load current I, depending on a number of factors, is distributed between generators I_1 and I_2 respectively.

The non-uniformity in the load distribution between generators (current imbalance) is characterized by the value of the lateral current I_q:

$$I_1 = \frac{I}{2} + I_q;$$

$$I_2 = \frac{I}{2} - I_q.$$

Evidently, with the uniform load distribution, the lateral current $I_q = 0$.

Let us examine the effect of individual factors on the character on load distribution between generators and the value of the lateral current:

The characteristics of the voltage regulators. The regulators may have a static or astatic tune-up.

Astatic regulators maintain the voltage unchanged within the bounds of the entire rpm revolution range of the generators $U = f(n) = \text{const.}$, which assures the uniform distribution of the loads between the generators operating in parallel, the other conditions being equal.

Regulators with a static tune-up and an identical statism have found practical application. With divergent characteristics, the loads are distributed non-uniformly with the exception of speeds, at which the voltage regulator tune-up was performed.

In as much as the rpm of the aircraft engines during flight is almost the same, and changes practically simultaneously, it is permissible to install voltage regulators with a statism up to $\pm$ 0.5 v in the entire range of rpm variations.

When one of the generators is disconnected, it is required to disconnect the equalizing circuit, in the opposite case the voltage of the operating generators will decrease through the action of the equalizing coils.

The inequality of regulator tune-up voltages ($U_{10} > U_{20}$; $R_{1+} = R_{2+} = R_+$; $R_{1-} = R_{2-} = R_-$) is caused by:

a) incomplete coordination of the characteristics of the jointly operating voltage regulators;

b) poor precision in tune-up of regulators for equal voltages;

c) detuning of regulators in the process of operation;

d) effect of changing temperature conditions because of imperfections of temperature compensation.

With a disconnected circuit of the equalizing coils the following equalities are correct:

$$U_{10} - I_1R_{1+} = U_{20} - I_2R_{2+};$$

$$I_1 + I_2 = I;$$

$$I_{q0} = \frac{U_{10} - U_{20}}{R_{1+} + R_{2+}} = \frac{\Delta U}{R_{1+} + R_{2+}},$$

where I_{q0} - is the transverse current, characterizing the non-uniformity of load distribution between the generators with an open equalizing circuit.

The value of this current does not depend on the load, and is a constant value for the given regulator detuning. Even during idling, when $I = 0$, there exists a certain transverse current which is uselessly heating the generators. In this case, one of the generators' is operating under these motor conditions.

When the equalizing coil circuit is closed, the transverse current I_q decreases substantially ($I_q < I_{q0}$), since in this case the voltage of the generator carrying a greater load, decreases, while that of the generator carrying a smaller load increases.

Inequality of Resistances of the plus sectors of the generator circuits

$$U_{10} = U_{20};\ R_{1+} \neq R_{2+};\ R_{1-} = R_{2-}.$$

For powerful electric systems the wire resistances are very low (thousands of an ohm), therefore any deterioration of contact connections may result during operation to a considerable difference in the resistance of the plus sectors.

When the equalizing circuit is open, the generator load is distributed in inverse proportion to the resistances of the positive sectors of their circuits.

When the equalizing circuit is closed, due to the action of the equalizing coils, the non-uniformity of the load distribution between the generators is relatively small.

Inequality of Distributions of the negative sectors of the generator circuits ($U_{10} = U_{20}$; $R_{1+} = R_{2+}$; $R_{1-} \neq R_{2-}$).

The value of the transverse current with an unequality of the negative sectors is considerably greater than with the same unequality of the positive sectors.

With the unequality of the ballast resistances and the presence of the equalizing coils, the load between the generators is less uniformly distributed, than with an open equalizing circuit, therefore, it is necessary to observe strictly the equality of the balanced resistances. Deviations of not more than 5% are permissible.

4. Parallel Work of Several Generators of Equal Capacity.

With the parallel work of several generators, the voltage for each one of them is maintained constant by means of its own automatic voltage regulator. Evidently, for an uniform distribution of the load between them, it is necessary to carry out the conditions marked for the two generators.

Let us examine a practical instance of parallel work of generators, when one, having a high voltage, may be impermissibly overloaded, while the others are operating under an incomplete load.

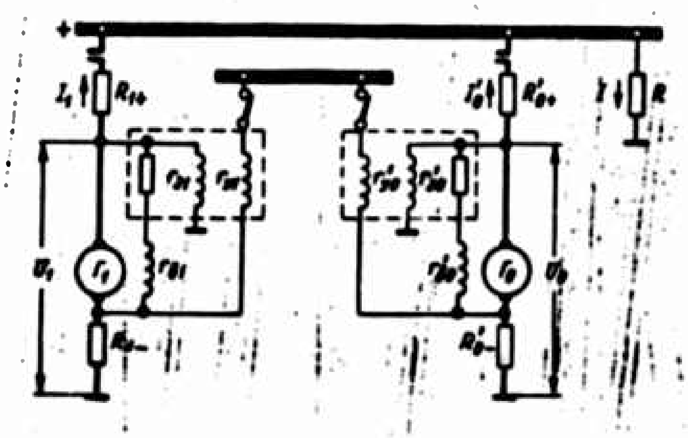

Fig. 4.3 Simplified circuit diagram of the parallel work of two generators of different capacities.

Let us assume that

$$U_{20} = U_{30} = \dots = U_{n0} = U_0; \quad U_{10} > U_0;$$
$$R_{2+} = R_{3+} = \dots = R_{n+} = R_{0+}; \; R_{1+} \neq R_{0+};$$
$$R_{2-} = R_{3-} = \dots = R_{n-} = R_{0-}; \; R_{1-} \neq R_{0-}.$$

Under these conditions, the parallel work of n generators may be considered as the work of two generators of different capacity, the diagram of which is given in fig. 4.3. The parameters of these generators will be as follows:

$U_{10}; U_0$ - are the voltages of the generator's tune-up;

$I_1; I'_0 = I_0(n-1)$ - are currents yielded by the generator;

$R_{1+}; R'_{0+} = R_{0+}\frac{1}{n-1}$ - are the resistances of the plus circuits of the generators;

$R_{1-}; R'_{0-} = R_{0-}\frac{1}{n-1}$ - are the resistances of the minus circuits of the generators;

$r_i = r_0; \; r'_0 = r_0\frac{1}{n-1}$ - are resistances of the equalizing coils;

$r_{e1} = r_e; \; r'_e = r_e\frac{1}{n-1}$ - are resistances of the operating coils of the voltage regulators.

Evidently, to distribute the load between the generators in proportion to their rated capacity, the resistances of the plus and minus circuits of the generators should be inversely proportional to the capacity of the generators:

$$\frac{R_{1+}}{R'_{0+}} = \frac{R_{1-}}{R'_{0-}} = \frac{P'_0}{P_0} = n-1.$$

Here, $U_{10} = U_0$; $R_{1+} = R_{0+}$; $R_{1-} = R_0$; $I_{qn} = 0$. If these conditions are not fulfilled, the transverse current originates.

With the parallel work of n generators of equal capacity, the value of the transverse current may reach a double value of the transverse current of the work of two generators operating in parallel.

With an arbitrary load I, of the power system the extent of the over load of the over excited generator is determined by the relative overload coefficient:

$$K_n = j + \frac{\Delta U}{R_{0+}\, I_{rated}}\; \frac{n-1}{1+\beta} - j\, \frac{\Delta R_+}{R_{0+}}\; \frac{1}{n(1+\beta)} - j\, \frac{\Delta R_-}{R_{0-}}\; \frac{\beta}{n(1-\beta)}$$

where $j = \dfrac{I}{I_{rated}}$;

$\Delta U = U_{10} - U_0$;

$\Delta R_+ = R_{1+} - R_{0+}$;

$\Delta R_- = R_{1-} - R_{0-}$;

β - is the coefficient which takes into account the number of coils and resistances of the operating and equalizing coils of the voltage regulators.

When there are deviations in the tune-up of the regulators, we cannot obtain the rated power from the electric power system equal to the total power of all the generators.

In connection with the above, in electric power systems with power work of n generators, we should use precise voltage regulators, possessing more stable parameters than in the work of two generators operating in parallel.

5. Parallel Work of Generators with Storage Batteries.

The parallel work of a generator with batteries is possible with:
1. Equality of voltages of the generators and batteries.
2. Equal polarities when they are connected to the collecting busbars.

In fig. 4.4 we present the circuit diagram of connections of the generator and battery during their parallel work.

In order to determine the distribution of currents during the parallel work of a generator with a battery, let us compare the external characteristics of the battery and the generator, operating with a voltage regulator. These characteristics are given in fig. 4.5.

In a generator, supplied with a voltage regulator with an astatic tune-up, the external characteristic in a wide range of load current variations, will be parallel to the axis of the abscissae (curve 1). And in a battery the characteristic drops rapidly with the increase of

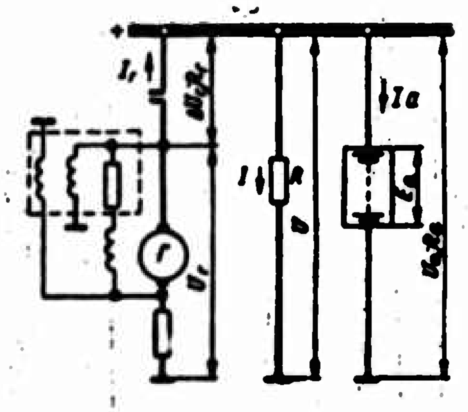

Fig. 4.4. Circuit diagram of the connections of the generator and storage battery during their parallel work:
U_r - is the voltage between the plus terminal of the generator in the mass;
I_r - is the current yielded by the generator into the power line;
R_r - is the resistance of the sector of the circuit from the plus terminal of the generator to the plus busbars;
E_a - is the electro-motive force of the battery;
I_a - is the battery current (positive during discharge and negative during charge);
R_a - is the resistance of the entire circuit of the battery between the positive busbar and the mass;
U - is the voltage at the collecting busbars;
I - is the load current;
R - is the load resistance.

the load current. For convenience of graphic plotting, the external characteristic of the battery is turned with respect to the axis of the ordinates by 180° (fig. 2). Taken into account the voltage losses in the connecting conductors, the characteristics are shown in bold lines 1' and 2'. Applicably to these characteristics we are examining the current distribution.

With a normal tune-up of the regulator, the voltage of the generator is always higher than the electro-motive force of the battery $U_r > E_a$. Under all the operating conditions the battery's feeder line is carrying the voltage of the collecting busbar $U_a = U$. Let us examine four characteristic cases.

1. The power system carries an all load I = 0, then $U_a = U_0 = U_r = \Delta U_{r0}$. In this case the generator is loaded only with the I_{r0}

current, going to recharge the battery I_{a0},

$$I_{r0} = I_{a0}.$$

2. The load I_1 is connected to the power system, the voltage at the collecting busbar decreases to U_1, then $U_{a1} = U_1 = U_r - \Delta U_{r1}$. In this case the generator is carrying the load of the power system and the current of the battery charge

$$I_{r1} = I_1 + I_{a1}.$$

3. The load in the power system is increased to I_2, so that the voltage at the collecting busbar drops to the value of the electromotive force of the battery $U_{a2} = U_2 = U_r - \Delta U_{r2} = E_a$. In this case the charging of the battery ceases and all the current of the generator goes to the power system load

$$I_{r2} = I_2.$$

4. The load in the power system is increased to I_3, so that the voltage at the collecting busbar drops to U_3, which is smaller than the electro-motive force of the battery $U_3 < E_a$. Then, $U_{a3} = U_3 = U_r - \Delta U_{r3} < E_a$. The battery is converted to the discharge regime. The load current becomes equal to the sum of the currents of the generator in the battery

$$I_3 = I_{r3} + I_{a3},$$

the share of the battery current increasing with the decrease of the generator's voltage.

In this way, the load current distribution between the generator and battery depends on their external characteristics, the battery being the consumer as long as $E_a < U$. Independently of the number of generators and batteries operating in parallel, the voltage on their common busbars is the same;

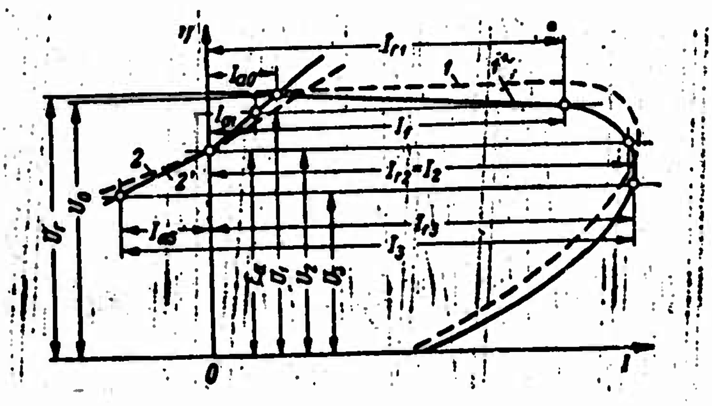

Fig. 4.5. External characteristics of the generator and battery.

$$U = U_a = E_{a1} - I_{a1} R_{a1} = \dots = E_{a\,n} - I_{a\,n} R_{a\,n} =$$
$$= U_{r1} - I_{r1} R_{r1} = \dots = U_{r\,n} - I_{r\,n} R_{r\,n},$$

the load current between them is distributed in accordance with the external characteristics and voltage on their common busbar.

The total current of all the generators operating in parallel is determined as

$$\sum_{k=1}^{n} I_{rk} = I \pm I_a.$$

The charging or discharging current of any battery is determined as follows:

$$I_a = \frac{E_a - U}{R_a}.$$

The most charged battery has a characteristic which passes higher than that of a discharged one, and has a less descending nature. Consequently, the battery which is charged the most consumes a smaller charging current and aids the generator when the voltage at the collecting busbar is higher.

When the battery is being charged with a direct current, the increment of capacity depends on the residual capacity, the temperature of the electrolyte, and the length of charging.

Approximately, the capacity increment in % may be determined according to V. S. Kulebakin's formula

$$\Delta q\% = [30 - 0.17\ q_{res}\%]\ \frac{25+\nu}{50}\ \sqrt{t},$$

where t - is the charging time in hours $t < 3$;
q_{res} - is the residual capacity in % of the rated capacity;
ν - is the temperature of the electrolyte ($\nu > 25°C$).

However, we should bear in mind that the power system aboard the aircraft having a rated voltage of 28.5 v, does not provide for a complete charge of 24 v batteries, since to restore the complete capacity a line voltage of 30 - 32 v is required.

Chapter 5. Diagrams of Primary Direct Current Power Systems.

1. Protection of Generator Busbars and Connecting Lines.

In d-c power systems the current protection with fuses and thermal automatic devices is being widely used. In fig. 5.1 we present four possible variations of current protection diagrams for generators busbars and connecting lines against short-circuit. The rated current of the fuses (protective automatic devices) is taken at 1.2 to 1.3 of the rated current of the generator. Upon a short-circuit at one of the busbars, the fuses at all the lines connecting this busbar with others, should operate. The selectivity of the protection device's work depends on the circuit diagram of the busbars.

Diagram a. With identical sources, connected to the busbars 1, 2, and 5, during a short-circuit at any of the busbars, the 1 to 5 currents in all the lines, connected to the damaged busbar, are approximately the same and equal to the generator current, which under stabilized conditions usually does not exceed the rated current. Consequently, the fuses in the lines do not operate during a short-circuit on the busbars.

Diagram b. When there is a short-circuit in the busbar, the current in its connecting line is equal to the sum of the currents connected to the operating busbars. As a result of this, the fuse in the line, leading to the busbar with the short-circuit will burn out first and will selectively disconnect from the other busbars.

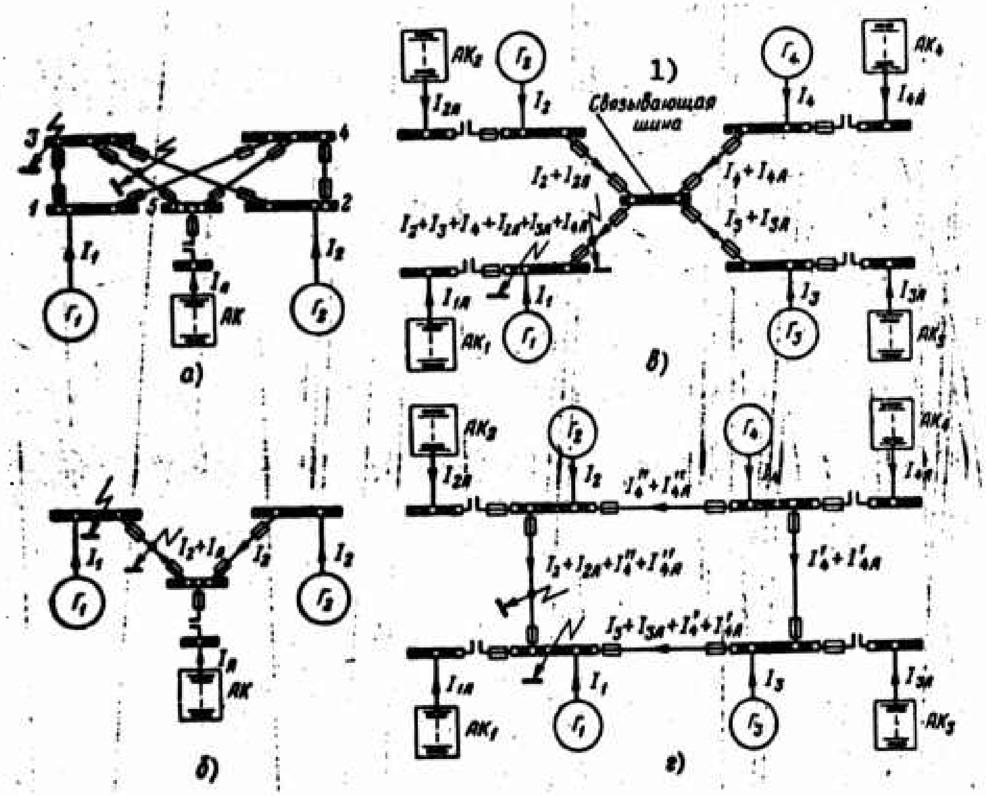

Fig. 5.1. Protection of the generator busbars and connecting lines during a short-circuit.
Key: 1. connecting busbar; AK = battery; r = generator.

Diagram c. When there is a short-circuit at the busbar, the current in its connecting line is equal to the sum of the currents of the other lines, consequently, the fuse in the line going to the busbar with the short-circuit, will burn out first and selectively disconnect from the remaining busbars.

Diagram d. When there is a short-circuit in the busbar, the current in the line leading to it is three times greater than in the other lines. Because of this, the protective device will selectively disconnect the busbar with short-circuit.

System c, provides for a rapid action, and system d, assures a high reliability of the feed source unit when there are breaks or short circuits in the supply lines.

In all the diagrams during a short-circuit in the line, the protective device operates selectively, disconnecting the damaged line from the system in working order.

Individual cases of damage to voltage regulators cause a considerable rise in the voltage in the power system in comparison with the rated voltage, which might result in putting out of order a number of consumers with serious emergency for the aircraft, therefore, the power systems should provide a protection against over-voltages.

2. Direct-Current Power System with a Radial Supply Network.

In fig. 5.2 we present the block-diagram of the d-c power system with a radial single channel protected supply-lines.

The principal sources of energy are two starter generators GSR-ST-6000 A, in combination with voltage regulators R-25A, and differential-minimum relay DMR-400A. The auxiliary source of power is the storage battery 12-SAM-28.

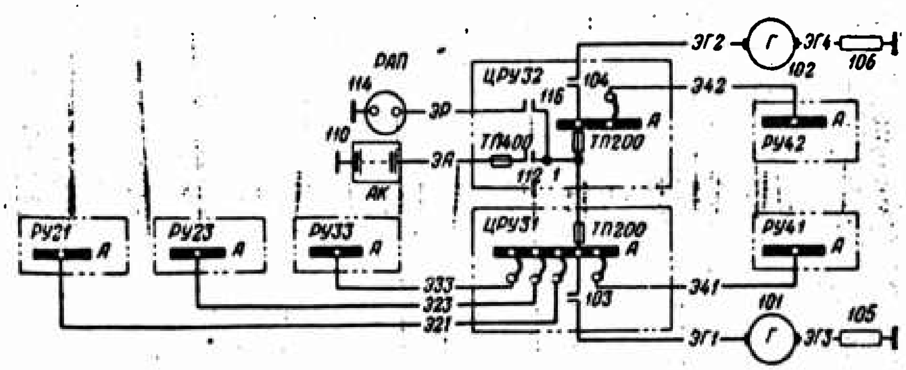

Fig. 5.2. Diagram of the d-c power system with a radial supply network.

The system provides for a one-sided, single-channel supply of the distribution busbars 21A, 23A, 33A, 41A, 42A, and a two-sided, single-channel supply of distributing busbars 31A and 32A.

During emergency conditions, depending on the character of the damage, the following phenomena may be observed:

1. During breaks and short-circuits in the supply lines of the busbars, all the consumers connected to the corresponding busbars lose current.

2. Short-circuit currents in the distributing busbars reach 800 to 1500 A, and at the distance of 1 m from the circuit-breaker, 1500 to 1700 A, exceeding the breaking capacities of the circuit breaker.

3. During a short-circuit at point 1, both differential-minimum supply systems (103, 104) pass into the bell conditions, and the contacts of the differential-minimum system might stick. After 10 to 12 seconds the TP-200 fuses operate and then the TP-400. The transition processes are accompanied by a major voltage dip. After the fuses burn out, the voltage in the supply system is restored, and the power system is converted into two isolated systems with the distributing busbars supplied from the corresponding generators.

4. During a short-circuit at the 31A busbar, we observe the bell condition in the differential-minimum supply system. After 2 to 3 sec. the TP-200 fuse of this busbar burns out, and then busbars 32A and 42A retain their working capacity, being supplied from the 102 generator and 110 battery. If fuse TP-200 burns out first at busbar 32A and further at busbar 31A, then busbars 32A and 42A receive their supply only from the 102 generator.

5. When there is a short-circuit at the 32A busbar, events occur which are similar to those mentioned in paragraph 4, and accordingly the working ability of busbars 31A, 21A, 23A, 33A, and 41A are retained, being supplied with power from generator 101 and battery 110, or only from the generator 101.

Because of the short-comings mentioned, the power system does not assure a reliable uninterrupted power supply into the consumers under emergency flight conditions, and in this form is not recommended for use in aircrafts, however, the principle of radial feed supplied to the distribution systems of secondary consumers may be used in planning.

3. Direct-Current Power Systems with a Main Power Supply Line.

In fig. 5.3, we present the simplified circuit diagram of a d-c power system with a main, single-channel protected power supply network and reserved feed for the emergency distribution busbar 22B.

The principal energy sources are two starter generators GSR-ST-12,000 in combination with voltage regulators RUG-82 and differential minimum relay DMR-400A. The auxiliary energy sources are two storage batteries, 12-SAM-28.

The main distributing device has two busbars: the main 22A, and the emergency 22B.

Under normal working conditions the 22B busbar is connected with conductor 115 to 22A busbar, but when the conductor breaks down, the 22B busbar does not receive any power supply. When the voltage disappears on busbar 22A (break or short-circuit) the time relays 119 and 120 are released, the conductors 117 and 118 operate, and the emergency busbar 22B is converted to feed from the reserve system (EG5; EG6).

WORK OF THE POWER SYSTEM DURING CONDUCTOR BREAKS:

1. When the E1 conductor breaks, the principal busbar 22A, is left without current, depriving of feed the corresponding group of consumers. The emergency busbar 22B is converted to feed from the reserve system.

2. When wires E' and E" are broken, both generators are disconnected from the system.

WORK OF THE POWER SYSTEM DURING SHORT-CIRCUITS:

1. When there is a short-circuit at the busbar 22A or wire E1 the fuse TB-400 operates. The main busbar is left without current. Busbar 22B receives feed from the reserve system.

2. When there is a short-circuit at the busbar 22B, conductors 115, 117, 118 go into the "bell"-working conditions and are welded shut. The feeding of the busbars goes through wires E1, EG5, and EG6. Fuses TB-400 and IP-100 burn out. Busbars 22A and 22B are deprived of current, leaving all the consumers without feed.

3. When there is a short-circuit in point 1, fuse IB-250 at busbar 42A burns out. During small rpm, the short-circuit current of the generator is sufficient for burning out the IP-250 fuses at the generator. The differential-minimum supply systems DMS-400 go into the "bell" operating condition and their conducts may weld together. The entire system, including the emergency system, remains short-circuited.

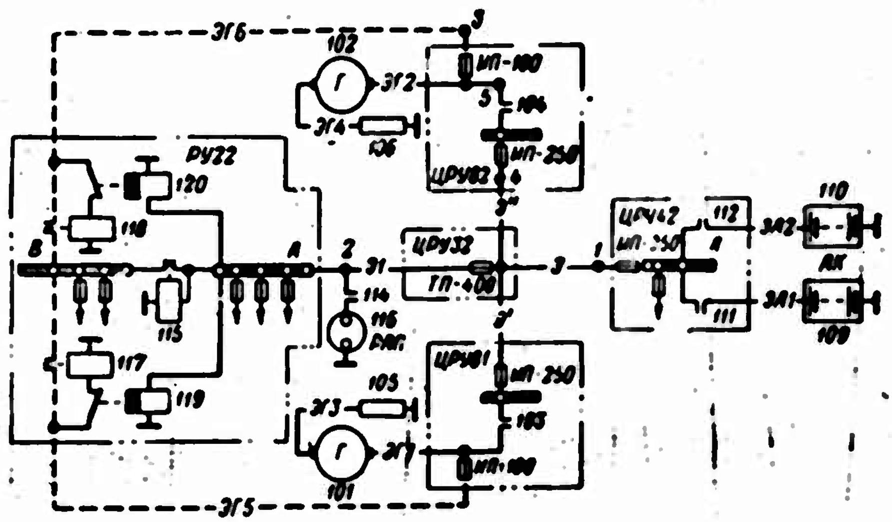

Fig. 5.3. Diagram of a d-c power system with a main supply network.

4. When there is a short-circuit at point 3, the DMS of the 102 generator is disconnected; the latter continues to feed the short-circuited point. The IP-100 fuse burns out. The DMS again connects the 102 generator to the system.

5. When there is a short-circuit at point 4, DMS-104 goes into the "bell" operating condition. The IP-250 fuse burns out; the rest of the protective system may not operate, and in this case the system will remain in the short-circuit state.

6. When there is a short-circuit at point 5, the DMS disconnects generator 102 from the system. The generator operates to supply the short-circuited point.

7. When there is a short-circuit at busbar 42A the battery unit goes out of commission.

The introduction of the automatic reservation of the emergency busbar supply circuit makes the system more complicated and heavier, but does not assure uninterrupted feed of the consumer when there is a break or short-circuit in the wires and distributing busbars. The reserve wires EG5 and EG6 are not used efficiently.

4. Direct-Current Power System with Radial-Main Reserved, Protected, Supply Lines.

In fig. 5.4 we give the simplified circuit diagram of a d-c system with a radial-main reserved, protected supply lines.

The principal energy sources are two generators GSR-12,000, operating in combination with voltage regulators R-25A and differential-minimum relay DMR-400. The auxiliary energy source is the storage battery 12-SAM-53.

The power supply system consists of primary and secondary distributing busbars. The secondary busbars are in two sections, each section receiving independent feed from primary busbars. A bilateral supply system for the feed line with fuses and contactors, the windings of which are supplied from the line protected through protective automatic devices and their switches, is provided for.

Advantages. 1. The system is relatively simple with respect to its arrangement and provides for laying the wires to the sections' distributing busbars along different sides of the aircraft, which improves appreciably the vitality of the system.

2. The distributing busbars 12A, 12B, 21A, 21B, 52A, 52B, supplying the main mass of consumers, are located in the crew's cabin, to assure convenience of preparation and operation of the system.

3. The radial feed of the secondary distributing tiers, makes it possible to assure easily the selectiveness of their protective operations.

4. In case of a break or a short-circuit in the main feed line of the secondary distributing busbar, the feed is automatically switched over to the operating line.

EXAMPLE. When there is a short-circuit in wire E11, the fuse IP-250 burns out, the conductor KM-200D is released, and conductor KM-200D is turned on, providing feed to busbar 12A over channel E12.
The switching-over to the other channel when there is a short-circuit in the wires of the remaining secondary distributing busbars is similarly assured.

Short-Comings. 1. When there is a short-circuit at busbar 12A there is a deep drop of voltage, which causes KM-200D to balk, resulting in the centering of the contacts. Thereupon conductor KM-200D operates and since the protective system is selective, IP-100 burns out. Busbar 12A is deprived of current, but the protection does not always operate selectively through the change in the characteristics of the fuses, when the short-circuit current passes. In this case, both busbars are deprived of current.

The processes during a short-circuit at other secondary distributing busbars proceed analogously.

2. When there is a short-circuit at the 52A(52B) busbar, the process occurs analogously to the one marked in paragraph 1, moreover, it is possible that KM-200D would pop, and the 42A busbar would be deprived of current.
3. In case of a short circuit in the wires with the IB-250 near 31A(32A), the DMR conductors will "flop". Fuse IP-250 then operates and the "flopping" stops.
4. In case of a short-circuit on busbar 31A(32A) the voltage at the generator conducts decreases to 0.8-1.6 v, the DMR goes into the "bell" mode. A current of 500-575 A flows from the generator, the DMR conducts are welded and fuse TP-600 does not operate. The circuit remains shorted. Fuses TP-400 burn out, disconnecting the batteries from busbar 31A (32A).
5. In case of a short-circuit in wire EG5, the DMR enters the "bell" mode, its conducts are welded and the DMR and generator are put out of order.
6. In case of a short-circuit in wire EG1, the DMR disconnects the short-circuit current from the line, and the generators continues to supply the short circuit point.
7. A main mass of consumers, including power consumers, are fed from the distributing busses of the crew's cabin, which considerably increases the weight of the consumers' wiring.
8. Stable short-circuit currents reach 1500-4000 A and represent a serious fire danger. The maximum current values are in the battery busses.

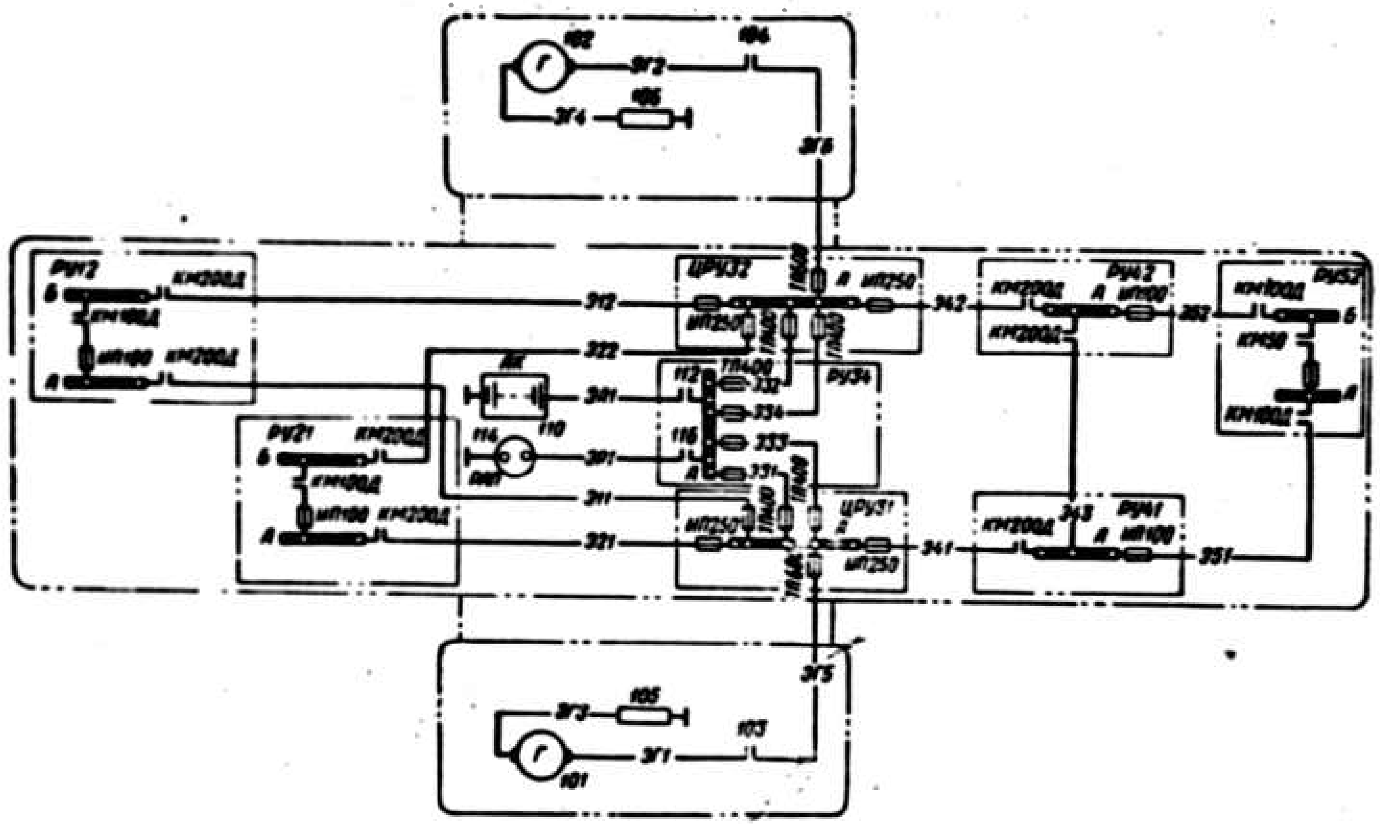

Fig. 5.4. Diagram of d-c power supply with radial main line cover, reserved, protected feed network.

CONCLUSIONS

1. The system has high survival and reliability characteristics for the distributor devices due to the two-sided protection, reserved power switching and placement of connectors in various sites.

2. In case of a short-circuit in the busses of the distributors, the contacts go into the "bell"mode, leading to melting of contacts.

3. The greatest fire danger results from a short-circuit on the primary distributing busses.

The system has high survival ability and reliability in comparison to others analyzed, but the defects noted, limit its range of application.

5. Direct-Current Power System with Combined, Unprotected Supply Network.

Figure 5.5 shows a diagram of a power system for d-c with combined, unprotected feed network, including elements of radial main line and closed circuits.

The principal power sources are four type GSR-18,000 generators in combination with a RUG-82 voltage regulator and a DMR-600 differential-minimum relay.

The reserve power supply is a type 12-SAM-53 battery, which can be connected to the main or emergency network.

The power system consists of two supply lines:

1. The principal system, including the main, multi-channel unprotected ring with the primary distribution busbars and the radial system with secondary distribution busbars.

2. The emergency system of the radial unprotected type.

Advantages. 1. The closed, multi-channel arrangement of the principal system provides for the uninterrupted power supply to consumers when their wires are broken at any point of the supply ring.

2. When the generators go out of order the 22B and 24B distributing busbars are connected manually to the storage battery, which provides power supply to instruments and small capacity consumers of the control system.

Short-Comings. 1. When the generators are short-circuited the voltage at their terminals drops to 0.8-5.0 v.

2. When there is a short-circuit at the generator-DMR sector, the generator is disconnected from the system and supplies the short-circuit point.

3. When there is a short-circuit at the DMR-system sector, the DMR goes into the "bell" operating conditions, their contacts are welded to one another and the short-circuit point is supplied from all

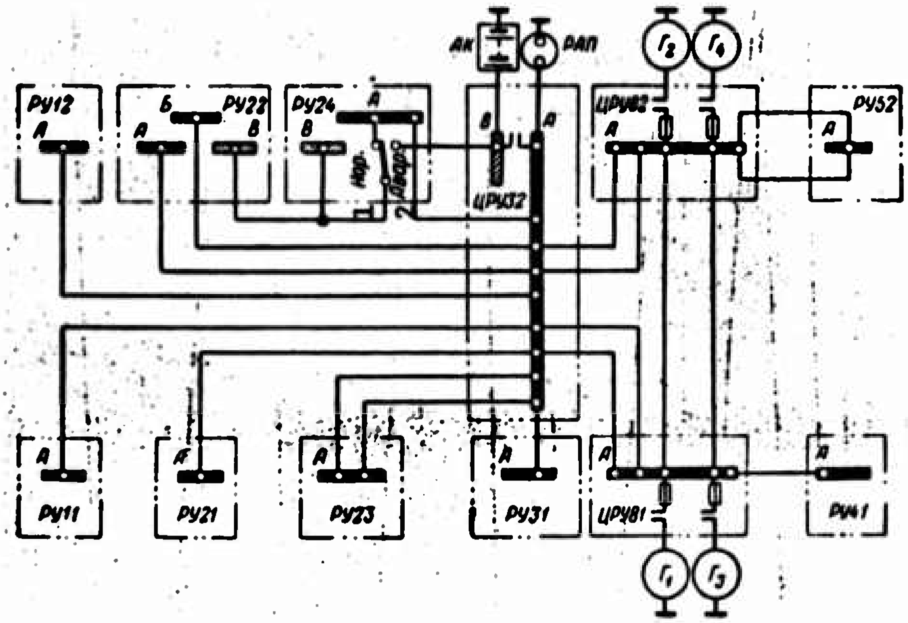

Fig. 5.5. Diagram of the d-c power supply system with combined unprotected power supply lines.
Key: 1. normal, 2. emergency.

the power supply sources. The entire system becomes short-circuited.

4. When there is a short-circuit at any point in the ring or radial lines, and also at the distributing busbars, the phenomena mentioned in paragraph 3 take place.

5. When there is a short-circuit at the sectors of the power supply system, which are at a considerable distance from the feed sources, the voltage at the generators' terminals does not drop below 5 v, and the DMR conducts to not "pop", however, the system is short-circuited.

6. Due to the large total power of the energy sources, the established currents during metallic short-circuits, reach 5,000-7,000A. Such currents are extremely dangerous as a fire hazard for the electric power system and the aircraft as a whole. The enormous short-circuit currents increase the probability of origination of a fire during the alternating short-circuits also.

7. The emergency system is built without protective devices and possesses short-comings which are inherent in the main system.

CONCLUSIONS

1. The principal system is not protected, it has a considerable length, which is the cause of its easy vulnerability during short-circuits.

2. During any kind of short-circuit the system goes out of order and a fire is possible.

3. The system retains its vitality only when the wires are broken without the short-circuit, but this type of damage is highly improbable.

4. The presence of an emergency system increases somewhat the reliability of the power supply, however, the short-circuit takes out of commission even the emergency system.

6. Direct-Current Power Systems with Angular, Multi-Channel, Protected, Power Supply Systems.*

In fig. 5.6 we present a diagram of a d-c power system with an angular, multi-channel, protected power supply line.

The system has a two-channel protected primary ring with primary distribution busbars 41A, 42A, 43A, and 44A, located in the corresponding central distributing systems, and secondary multi-channel protected rings with distributing busbars 21A, 21B, 21C, 22A, 22B, and 22C, located in the corresponding secondary distributing systems RU 21 and RU22. The quantity of the primary and secondary distributing devices is determined by the conditions of the lay-out and location of the sources and their consumers of electric power.

The principal sources of power are the four starter generators (G_1- G_4). The generators deliver energy to their own main busbars A, which are the primary distributing points in the system.

The batteries serve as reserve sources and are connected directly to their own busbars B, which are connected with the main busbars of the generators, by means of conductors. The battery busbars 42B and 44B are connected also with the emergency busbars 21C and 22C.

Under normal operating conditions, all the distributing busbars receive feed from generators, the batteries are being rescharged from the power lines and at the same time are serving as a damper for removing brief peak-loads.

The angular multi-channel feed system preserve practically the viability of the system to the last energy source during multiple short-circuits and breaks in the feed lines. It is precisely for this reason, that in this diagram the role of the emergency system is reduced only to work under extreme conditions, i. e., during the failure of all the generators, when only the batteries are the only energy sources.

* Developed by the author in 1950 - 1953.

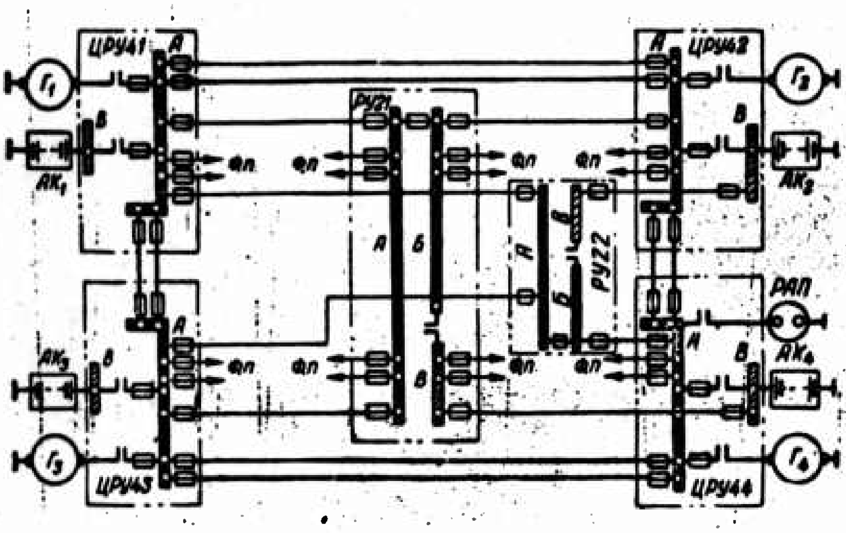

Fig. 5.6. Diagram of a d-c power system with a manual, multi-channel protected supply network with four generators.

When all the generators fail (a case which is little-probable in actual practice) the especially important consumers, which are indispensable for landing or continuing flight (if the aircraft engines are working), switch over automatically to feed from the emergency busbars B, i.e., directly from the batteries.

The emergency busbars B in many secondary distributing devices, receive their power supply through one of the main channels directly from the battery busbars. The emergency busbars are disconnected from the main system automatically by means of a voltage relay, tuned up to the rated voltage of the main busbar of the generator, or manually by setting the battery-switch into the "emergency conditions" position.

A similar system may be successfully used in medium and heavy aircraft with any number of aircraft engines.

In fig. 5.7 we present a circuit diagram of a d-c power system with angular, multi-channel, protected, power supply lines with two starter generators. The principle of these systems' design is analogous to the ones examined. The primary busbars of CTS11 and CTS12 are separated into sections and connected to the common power supply line. Under emergency conditions, the B-busbars are disconnected automatically or manually by the conductors from the A-busbars, and in this case the batteries will supply only the emergency busbars. The system may be used successfully for an aircraft with one or two eninges.

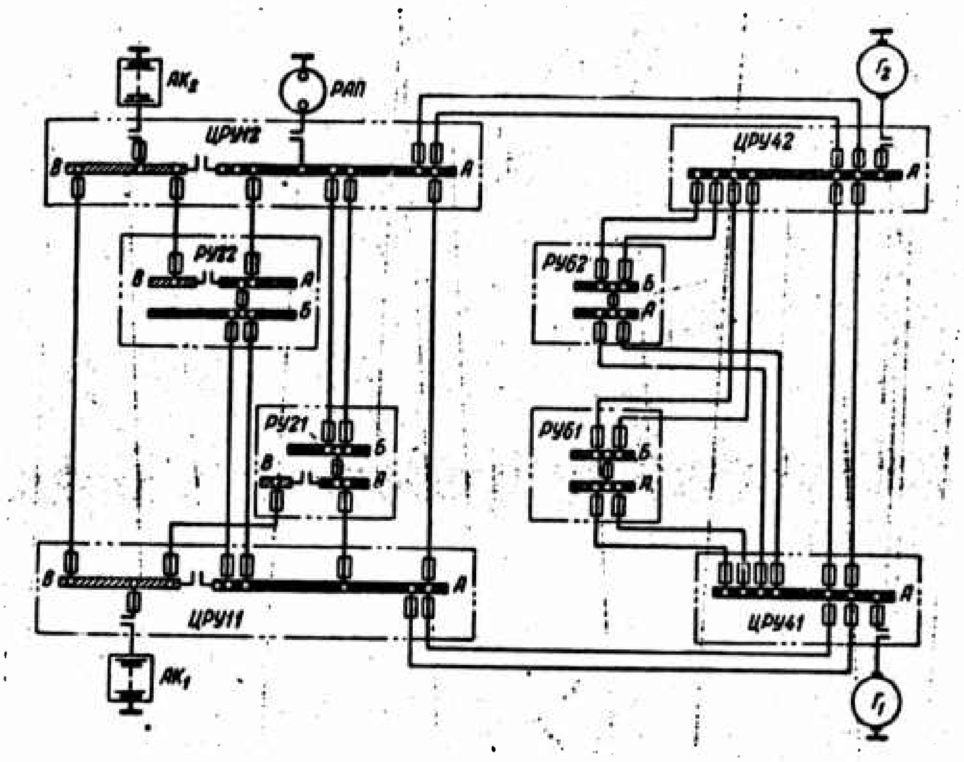

Fig. 5.7. Diagram of a d-c power system with angular, multi-channel, protected, power supply system with two generators.

In fig. 5.8 we present a circuit diagram of the d-c power system with an angular, multi-channel, protected power supply system with two starter generators and reservation of the emergency system. The system is analogous to the one given in fig. 5.7. To supply the emergency busbars under emergency conditions, the reserve wires are used, which results in an increase of the system's weight, therefore the use of reservation is permitted only for aircraft which have specific operation conditions.

In angular systems, to supply the busbars of the secondary distributing systems, serving the auxiliary consumers, the use of radial, protected power supply lines is permitted.

The angular, multi-channel protected power supply systems, as it has already been noted, assure the highest reliability and vitality under normal and emergency operating conditions of the power system, and are the most promising for the aircraft in the design stage.

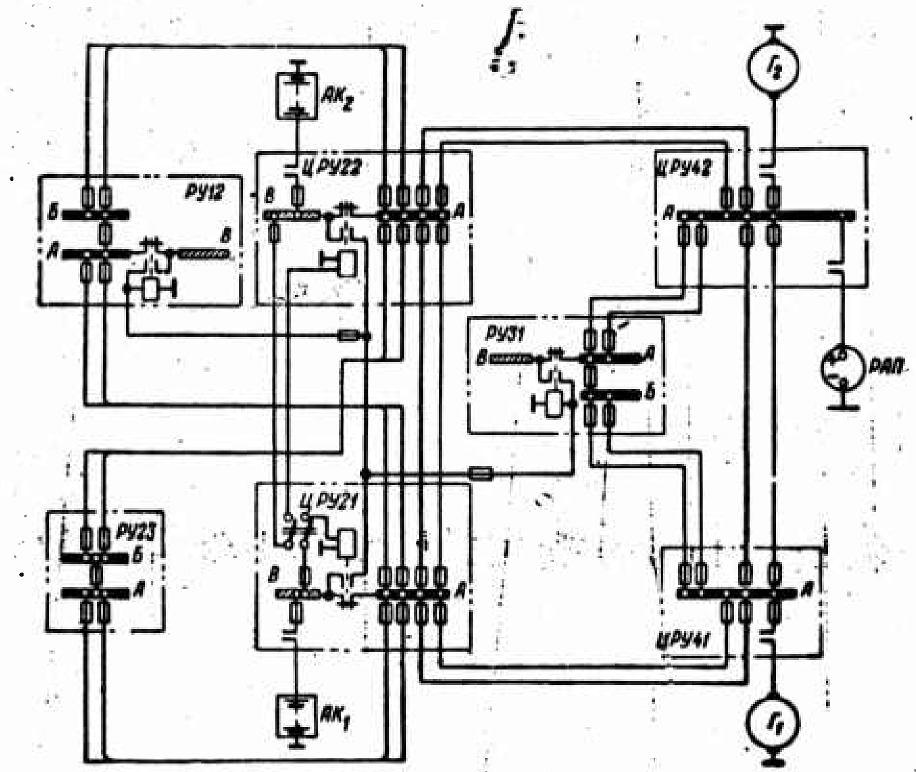

Fig. 5.8. Diagram of d-c system with an angular, multi-channel, protected, power supply system with reservation of the emergency system.

Section V. Primary Alternating-Current Power Supply Systems.

Chapter 1. General Information on Alternating-Current Power Supply Systems.

1. Specific features of Alternating-Current Systems.

The continuous growth of the speed and flight-ceiling, the increase of capacity and variation in the character of the consumers' work, makes it necessary to use a-c as the principal type of electric energy in the primary power supply systems. The analysis of the electrical equipment systems of aircrafts indicates that about 95% of electric power consumers can operate with alternating-current.

The use of alternating-current with a voltage of 200/115 v, in comparison with direct-current with a voltage of 27 v, yields a number of advantages:

1. The weight of electrical equipment on the aircraft decreases by about 30% to the simplification of the design, reduction of the dimensions and weight of the generators, transformers, power lines, part of the consumers, and the cooling system.

2. The reliability and quality of electric power supply to the consumers is raised through: absence of collectors and contact rings at the generators and electric motors, elimination of rotating converters for supplying the radio-electronic and navigation equipment, increase of the flight ceiling, decrease of the total number of regulators and increase of regulation precision.

3. The technical-economic indices are raised through the increase of service life of the work-period provided for by the regulations and decrease of the weight.

4. The maximum power of the generators increases.

5. The voltages increases, which makes it possible to reduce the weight of the system and simplify the conversion in order to obtain the optimum voltage for the consumers.

6. The transformation of energy from the direct to the alternating current is simplified due to the use of semi-conductor rectifiers, which improve the reliability of the secondary power systems. In this case the capacity of the transformers into the direct-current does not exceed 5% of the installed capacity of the alternating-current and is carried out with high efficiency (0.8-0.9), whereas in the system of transformation of d-c into a-c about 20-30% of the power is transformed by the electrical machine transformers with lower efficiency (0.5).

7. The short-circuit current value decreases in comparison with d-c units of the same capacity.

8. The radio-reception noise level is lowered because of the absence of collecting devices.

The a-c system has also a number of short-comings:

1. Depending on the operating conditions of the aircraft engine the rpm of the generators varies within limits of 1:3, which results in deviation of the frequency within the same limits. Electrical energy with unstable frequency does not meet the requirements of all the consumers.

2. In order to obtain a-c with a stable frequency it is necessary to have constant speed drives, which are installed between the aircraft engines and generators and provide the constancy of the generators' rotation. The presence of an intermediate element results in an

increase in weight and reduction of the reliability of the system.

3. It is impossible to assure parallel work of the generators which are driven directly by the aircraft engines.

4. It is difficult to turn on the generators for parallel work and maintain it in connection with the necessity for a strict adherence to the equality between the rpm, coincidence of phases, and voltage values of the generators.

5. The uniform distribution of active capacities between generators operating in parallel, is possible only by acting on the generators' drive, i.e. by regulating their mechanical capacities.

6. It is difficult to regulate the rpm of asynchronous motors.

Thus, in spite of certain short-comings a-c with a voltage of 200/115 v with respect to the reliability and weight has undeniable advantages over 27 v d-c.

2. Principal Technical Requirements to A-C Power Systems.

The technical requirements to d-c power supply systems, electric power lines, and power systems, extend almost entirely to the a-c power systems.

Let us note certain specific features:

1. The shape of the voltage curve should differ from the sinusoid by not more than 5%.
2. The efficiency should be at its maximum under the operating conditions.
3. The total resistance of the generator to the inverse sequence-current should be not more than 0.2 decimal unit.
4. For a confident operation of the protective system, the short-circuit current should be: single phase - not less than $4I_{rated}$, and symmetrical three-phase - not less than $3I_{rated}$.
5. The precision in maintaining the frequency during the load changes from 0 to rated, with a drive without corrector, is $\pm$ (1-2)% and with a corrector $\pm$ (0.1-1)%.
6. The non-uniformity of distributional active and reactive loads between generators operating in parallel should be not over 5% of the rated load of a single generator.
7. The accuracy in maintaining voltage during changes in the symmetrical load from 0 to the rated load is $\pm$ 1-2%.
8. The non-uniformity in the phase-load of the generator should not exceed the phase capacity, and the voltage deviations of individual phases from one another should not exceed 3%.
9. The control equipment should provide manual switching on of the automatic equipment during the separate and parallel work of the generators, automatic asynchronization and disconnection of generators, when they go out of synchronism and in case of all types of faults.

10. The protective equipment should provide the following protection to the power supply systems:

a) against voltage increase to above 225 ± 5 v with an inverse-relation volt-second characteristics;

b) against voltage drop below 180 ± 5 v with a lag of 2 + 0.5 sec;

c) during deviation of the frequency by ±15% from the rated frequency with a lag of 5 sec;

d) against over-excitation and under-excitation;

e) against all types of short-circuits inside the generator or its feeder without a time lag. The protective system should not operate during a through-short-circuit current of up to $6I_{rated}$;

f) during all types of short-circuits in the main lines or distributing busbars of the power supply system with an inverse-relation volt-second characteristics;

g) during over-loads of the generator in case of non-uniform distribution of the active or reactive capacity;

h) during the conversion of the generator to the motor conditions due to a reduction of the rpm of the drive;

i) during deviations of the rate of rotation of the drive above the permissible speeds.

11. A control apparatus should be provided for: a voltmeter, frequency-meter, and watt-meter, which normally show the active capacity and when the button is pressed, the reactive capacity, and also pressure and temperature indicators of the hydraulic fluid or air used for supplying the constant speed drive.

12. The signaling equipment should produce a signal on the "generator failure" lamp when any type of protective device operates, and to the "non-parallel work" lamp when the generator goes out of synchronism.

Allowances for individual parameters are given tentatively and should be rendered more precise during the development of the specific system.

3. Selection of the Main Parameters of an A-C Power System.

The advantages of the use of an a-c power supply system are caused to a large extent by the correctness of the selection of its principal parameters: number of phases and their combinations, voltage, and frequency.

Number of Phases

Upon conversion to a single primary a-c power supply system, the consumers (especially with a capacity of over 0.5 kwA) should be made three-phase, since they provide for a uniform load of the phases and decrease the degree of asymmetry of phase in linear voltages.

In the three-phase system the degree asymmetry ϵ is characterized by the relationship between the inverse relation sequence U_2 and the direct sequence voltage U_1 and should not exceed 4%, i.e.,

$$\epsilon = \frac{U_2}{U_1} \cdot 100\% < 4\%.$$

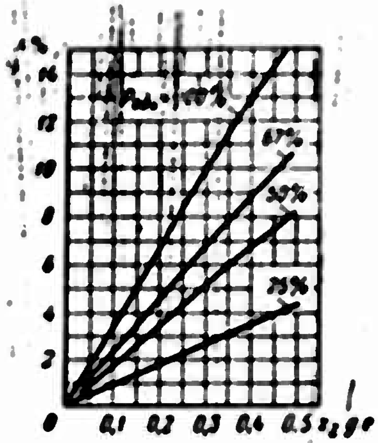

Fig. 1.1. Dependence of the degree of asymmetry on z_2 for various single-phase loads.

The extent of voltage asymmetry depends on the resistance of the generator to the inverse relationship current, and also to the resistance and nature of the load, having the maximum value for the capacity load and the minimum for the inductive load.

In fig. 1.1 we present the relationship of the degree of asymmetry of the three-phase generator's voltage to the resistance to its inverse relationship current for various single-phase loads (100, 67, 50, and 25% of the rated phase capacity).

From this curve we can see, that the limitations of the degree of voltage asymmetry limit proportionally the value of the resistance to the inverse relationship current. In actual practice z_2 is selected not greater than 0.2 decimal units.

The increase of the voltage asymmetry above 4% causes the appearance of a field rotating in the opposite direction in the asynchronous motors, which results in a decrease of the rotating moment at the motor's shaft, increase of losses, and deterioration of power indices.

A prolonged of three-phase generators under a non-symmetrical load is permitted, if the currents in the phases do not increase the rated value, and their difference does not exceed 10-20% of the rated current of the phase.

The capacity of the three-phase current consumers amounts to about 90% of the installed capacity of the consumers. The remaining minor one-phase consumers should be distributed uniformly according to the phases, taking into account their simultaneous connection. This makes it possible, to retain in actual practice the symmetry of the phase voltages, and in this way assure the high quality of power supply to the consumers.

The number of three-phase current consumers increases appreciably to the use of three-phase motors, which have better weight and power indices than the single-phase motors of the same power.

As the principal a-c system it is advisable to adopt the three-phase system with a grounded power neutral. In this case the single-phase consumers may be connected to the linear or phase voltage.

Voltage

In selecting the value of the rated voltage and its tolerances, it is necessary to take into account a number of factors:

1. Length of the power system and value of the power transmitted.
2. The consumers' feed voltage. For the majority of the consumers it is the most expedient to use the 200 v voltage for some 115v and only for an insignificant number of consumers (about 2% of the total capacity) voltages of 15, 27, 36 v, and others.
3. The reliability of the system's work under conditions of supersonic and high-altitude flights. The increase of the a-c voltage up to 200 v practically does not impair the conductivity of switching and arc extinguishing in comparison with direct-current.
4. The safety of the system for the operating personnel. A d-c voltage of 27 v and an a-c voltage with a frequency of 400-2,000 cps, not above 40 v is considered safe. Therefore, with the use of the alternating current with a voltage of 200/115 v, remote control should be used with a voltage not over 27-30 v at the control panels.
5. Weight of the generators, switching, and distributing equipment.
6. Size of the short-circuit currents.
7. Power quality and losses.

Today under all the operating conditions, the d-c generators assure the voltage variation within the limits of ± 2% of the rated voltage. However, from considerations of improvement of power supply quality and minimum losses in the power lines, this tolerance should be reduced to a value of not more than ± 1%.

The rated voltage at the consumers' terminals $U_{c.rated}$ and the tolerance for this voltage is determined by the rated voltage of the generator $U_{g.rated}$, the tolerance for its voltage $\pm \Delta U_g$ and the voltage loss in the power system ΔU_s

$$U_{c.rated} = U_{g.rated} \pm \Delta U_g - \Delta U_s.$$

The maximum voltage at the consumers' terminals is possible with the upper tolerance of the generator voltage ($+\Delta U_g$) and by connection of the consumers to the point of connection of the voltage regulator ($\Delta U_s = 0$):

$$U_{c.max.} = U_{g.rated} + \Delta U_g,$$

and the rated voltage, with the lowest tolerance of the generator's voltage ($-\Delta U_g$), and connection of the consumers at the point which is at the maximum distance from the point of connection of the voltage regulator, and with the maximum load capacity, connected in the power line examined ($\Delta U_s = \Delta U_{c.max}$):

$$U_{c.min.} = U_{g.rated} - \Delta U_g - \Delta U_{s.max}.$$

The tolerances for voltage fluctuations at the consumers' terminals are determined in the following way:

$$+\Delta U_c = U_{c.max.} - U_{c.rated} = U_{g.rated} + \Delta U_g - U_{c.rated}$$

$$-\Delta U_c = U_{c.min} - U_{c.rated} = U_{g.rated} - \Delta U_g - \Delta U_{s\ max} - U_{c.rated}.$$

Proceeding from the experience in the system of the three-phase a-c with the grounded power neutral, we adopt as the rated voltage: in generators 208/120 v ± 2-1% and in consumers 200/115 v ± 5%, as at once meeting most successfully the totality of all the requirements with respect to the weight of the power system, the electric machines, electrical things of insulation, reliability and operating safety.

The 36, 28, 15 and other voltages are obtained from the basic voltage by means of transformers or automatic transformers. In order to increase the quality of the output voltage, the transformer should be connected to the busbars, from which the sensitive elements of the voltage regulators receive their power supply.

Frequency

The outside dimensions, weight, and technical characteristics of the majority of electrical-system elements depend to a great extent on the frequency of the alternating-current. Optimum frequency values exist for each element.

However, individual frequency transformation may be reached only by means of complicated, heavy, and cumbersome rotating machines or ferro-magnetic frequency multipliers. Therefore, it is more rational to have a single frequency, which is optimum for the entire a-c system.

The criterion for the selection of the optimum frequency for a power system, we may adopt the miminum weight of individual elements and the entire electrical equipment of the aircraft.

The principal elements are: electrical machines, power transformers, radio equipment, and wires of the aircraft's power system.

Let us examine the effect of frequency on the weight of individual units.

The generators with electrical excitation have the optimum frequency of 300-500 cps, while those excited by permanent magnets have a frequency of about 800 cps [1].

We should note thereupon the change of frequency by the same value the weight changes differently depending on the rpms of the generator.

The electrical mechanisms are the largest electric power consumers and they occupy a considerable place in the weight of the electrical equipment. But they, as a rule, operate for a short period of time.

The most numerous and important are electrical mechanisms of the rotating type. The mechanisms which control the vitally important units, are built with a high reliability through the use of two electric motors, operating in parallel for the single reducing gear. When one motor goes out of order, the second fulfills successfully all the functions with a reduced rate of revolutions of the output shaft of the mechanism, using the differential in the reducing gear. Among these units are mechanisms, controlling the ailerons, stabilizes, chassis and a number of others. The weight of two motors amounts to 50-55% of the entire weight of the mechanism.

The greatest decrease in weight with a frequency of 400 cps and rate of rotation of 8,000-12,000 rpm amounts on the average to about 30% in comparison with direct current.

The increase of frequency above 400 cps results in a considerable increase in the weight and decrease of the efficiency and cos ϕ.

The above pertains also to electric motors operating during long periods of time.

In this way, for electrical motors operating at the rate of rotation of 8,000-12,000 rpm, 400 cps is the optimum frequency

In transformers, the weight and the outside dimensions are reduced with the increase of the frequency. When the frequency changes from 400 to 2000 cps, the weight of low power transformers is reduced by one-half and the power transformers by 1.3 times, since the latter are made with greater loads for the active materials than the low power ones.

With a higher frequency the efficiency of the transformer increases somewhat (up to 10% with 2,000 cps) since the reduction in the dimensions, in spite of the increase of specific loss in iron, results in a decrease of the loss in copper and iron. The dispersion and activity decreases and the stability of the output voltages increases.

RADIO AND RADAR EQUIPMENT

The frequency change affects the electric motors, potentio-meters, revolving transformers, relays, power transformers, condenser, filter choke coils, and a number of other elements. Power transformers have the greatest weight among them.

In rotating transformers the change in frequency from 400 to 2,000 cps increases the error in the reproduction of the sin-cos law and the change of the phase shift. Therefore, in spite of the possibility of reducing the weight and dimensions of rotating transformers, their conversion to a higher frequency is inadvisable.

The smoothing-out filters of the feed units and choke coils, consisting of L and C elements, lose weight with the increase of the frequency.

In this way, upon the increase of the frequency, the insignificant gain in weight of the radio equipment through transformers and their filters lowers appreciably the output parameters, which determine the quality of the work. Consequently, it is advisable to retain the 400 cps frequency.

For instruments and automatic devices, which include gyroscopic devices, magnetic amplifiers, potentiometers, rotating transformers, computing equipment, capacitance and inductive sensors, relays, low power electric motors, operating in tracking systems, as it is indicated above, it is not advisable to raise the frequency above 400 cps.

Magnetic capacitors, reduce appreciably the weight dimensions with the increase of the frequency, similarly to the transformers.

With the 400 cps frequency they have a considerable weight, approximately 100-150 g per 1 w of output power. The increase in frequency results also in the decrease of the time-constant of the capacitor. The feed of magnetic capacitors should be taken from the main power line through frequency multipliers. In general, the instrument equipment and their automatic devices, when they are converted to a higher frequency, will have the same weight as when they use a 400 cps frequency.

THE SWITCHING EQUIPMENT.

A change in the a-c frequency affects the arc extinguishing process at the equipment's conducts. The arcing time in the 400-600 cps frequency band is the minimum. In this frequency region, the increase in voltage at the contacts after the arc has been arrested, proceeds slower than restoration of the electrical strength of the air in the arc gap, therefore, having been quenched after the first passage of the voltage through 0, the arc does not form again.

The optimum frequency for the switching equipment work is 300-600 cps.

THE WIRES OF THE POWER SYSTEM ABOARD THE AIRCRAFT.

With the increase of the a-c frequency the active resistance of the wires, because of the displacement of the current increases.

This results in an increase of a voltage loss in the conductors and proportionally to the increase of the power lines' weight.

Wires with a cross-section of up to 10 mm^2 admit a considerable frequency increase without a noticeable resistance increase, while wires with a cross-section of 50-95 mm^2 even at the 400 cps frequency, increase their resistance by 10-15%.

A curve giving the example of the change in weight of the basic elements and the entire electrical equipment depending on the frequency is shown in fig. 1.2.

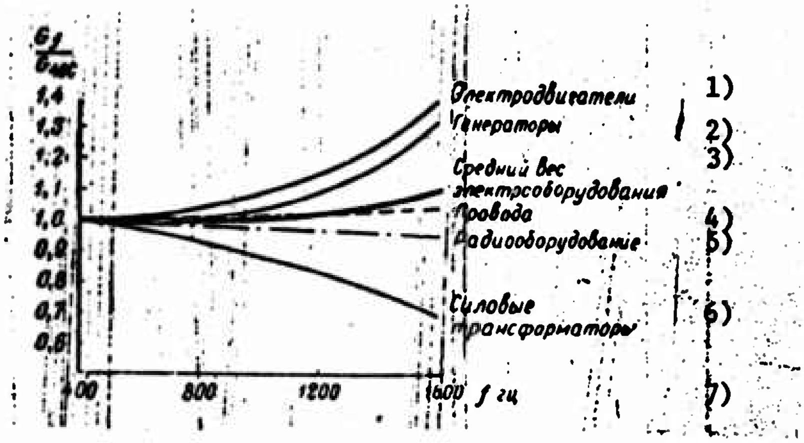

Fig. 1.2. Curve of the change in weight of electrical equipment, depending on the frequency.

1. Electric motors
2. Generators
3. Main weight of electr. equipment
4. Wires
5. Radio equipment
6. Power transformers
7. Cps.

FREQUENCY STABILIZATION PRECISION. Consumers may be divided into four groups with respect to the frequency stabilization precision required for their work.

1. Consumers, indifferent to frequency stabilization, such as devices against ice formation, heating of equipment, crew's equipment, lighting, and similar types of electrical equipment.

2. Consumers, permitting a rough frequency stabilization within the bounds of $\pm$ 5-10%. Among them are radio communication and radar equipment with respect to the main power used by them.

3. Consumers, requiring precise frequency stabilization, of about $\pm$ 1-2%. Among them are a wide variety of automatic, regulating, and computing devices, navigation instruments, and other equipment, for which the frequency stabilization precision worse than $\pm$ 1-2%, is inadmissible, because of the increase of the scattering of their output parameters.

Frequency stabilization precision not below $\pm$ 1% is also necessary for synchronizing the generators working in parallel.

4. Consumers, requiring precision frequency stabilization, of about 0.05-0.005%. These are mainly the navigation and computing devices, which have elements, by means of which it is required to syn-

chronize rotation with high precision, perform integration and differentiation operations, such as for example, synchronous motors in astro-navigational systems, which account for a time and distance. Due to the sufficiently long period of their work, the integration error with inexact frequency stabilization increases appreciably. The quantity of such devices is not large, and the power consumed by them is low.

Thus, in order to obtain optimum weight and work reliability parameters for the entire electrical equipment in the main a-c power system, we should adopt as the rated frequency 400 cps with a stabilization accuracy of $\pm$ 1%.

Consumers, requiring precision frequency stabilization (0.05 - 0.005% cps) should receive their power supply from special converters.

CONCLUSIONS

In the primary a-c power system it is advisable to adopt the following basic parameters:

1. Three-phase system with a ground power neutral.
2. Generator voltage of 208/120 v $\pm$ (1-2%).
3. Consumers voltage 200/115 v $\pm$ 5%.
4. Frequency 400 cps $\pm$ (0.1-1%).
5. It is advisable that consumers with a capacity of more than 0.5 KvA would be of the three-phase type.

In this case the single-phase consumers with a voltage of 115 v are supplied with power from the main power line using a power neutral. Consumers with a voltage, differing from the main one, are supplied through transformers. The precision frequency consumers are supplied from special converters.

4. Classification of A-C Generators.

A-C generators are classified as: synchronous with electro-magnetic excitation, magneto-electric with excitation from permanent magnets, and inductor generators with electro-magnetic excitation or excitation from permanent magnets.

Synchronous generators with electro-magnetic excitation are made as a rule with internal sharply expressed poles, and are the principal sources of energy in the primary and secondary electric power systems.

Magneto-electric generators are used as exciters of synchronous generators and the transformer generators in the secondary power systems. Their principal merit is their high reliability, simplicity of design and servicing (because of the absence of sliding conducts, brushes, and rotating excitation winding), independent action, and high efficiency (because of the absence of loss for excitation in the sliding conducts).

Inductor generators are used mainly in convertors of the MA type.

THE SYNCHRONOUS NON-CONDUCT GENERATOR WITH SELF-EXCITATION. In recent years, for aircraft power systems, non-conduct a-c generators were developed, which include three main elements: sub-exciter, exciter, and generator. The possible variation of the circuit diagram of a non-conduct a-c generator is given in fig. 1.3.

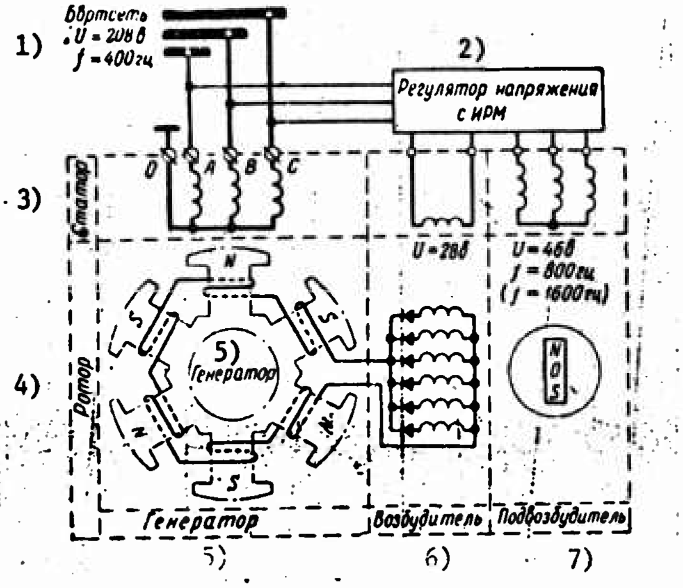

Fig. 1.3. Diagram of a non-conduct synchronous generator with self-excitation. Key: 1. aircraft power system, 2. voltage regulator with IRM, 3. stator, 4. rotor, 5. generator, 6. exciter, 7. sub-exciter.

The sub-exciter consists of a machine with excitation from permanent magnets, which are located on the rotor. The sub-exciter generates a small, single-phase (or three-phase) power with a frequency of 1600 cps (or 800 cps), which is used for supplying the control, regulation and protection equipment.

The excitation winding of the exciter is placed in the stator, and obtains its power supply from the sub-exciter through a rectifier.

The exciter's rotor has a multi-phase winding, connected through silicone rectifiers with the rotating windings of the excited main generator.

The a-c energy with a frequency of 400 cps is removed from the windings of the main generator, located on the stator. The non-conduct generator does not have conduct-rings and brushes.

The above described excitation system imparts to the generator an exceptionally high stability, while the use of the sub-exciter and exciter makes it possible to select the optimum operating frequency of the stabilizer and reduce substantially the length of the transition processes in the entire system.

The principal technical data of the three-phase a-c generators are given in table 1.1.

Chapter II. Constant Speed Drives.

1. Classification and the principal technical requirements for constant speed drives.

Depending on the flying conditions, the rate of rotation of aircraft engines varies within wide limits (in TVD 1 - 1.3, in TRD 1 - 2.8). In this case, the speed of the generators driven by the aircraft engine through the usual mechanical reducing gear, also varies within these limits.

The rate of rotation of the generator is stabilized by means of a constant speed drive (CSD), which the connecting link between the generator and the aircraft engine, regulating smoothly the transmission ratio between the aircraft engine and the generator.

With respect to their operating principle the constant speed drives are classified as mechanical, hydraulic, pneumatic, and electrical, and with respect to the branching of the flow of energy, transmitted from the aircraft engine to the generator into simple and differential.

In a simple drive the entire energy taken from the primary motor, is first transformed qualitatively and transmitted in only one direction, from the primary motor to the generator.

In the differential drive, the mechanical energy, taken from the primary motor, is transmitted to the generator in the way: directly without transformation through the mechanical reducing gear with a high efficiency and with qualitative transformation through a regulator. This part of energy may vary with respect to value and also

Table 1.1: Principal Technical Data of Three-Phase A-C Generators.

1 Тип генератора	2 Номинальные данные: мощность $P_{ном}$, ква	4 напряжение U, в	5 ток I, а	6 скорость n об/мин·10³	7 частота гц	cos φ	8 Возбуждение: U, в	I, а	9 Вес, кг	10 $G/P_{ном}$, кг/ква	11 Высотность H, км	12 Расход и давление воздуха, дм³/сек и мм вод. ст.	13 Габариты: 14 диаметр, мм	15 длина, мм	16 Число полюсов	17 Соединение обмоток	18 Регулирующая аппаратура: 19 регуляторы напряжения	20 коробки управления и регулирования	21 точное регулирование напряжения	22 защита от перенапряжений	23 выносное сопротивление
СГС30У	30,0	120	144	8,0±2%	400±2%	0,85	26÷30	29,0	39,0	1,3	—	235/400	198	443	6	*	РН-600	КРЛ-33А			ВС-34
ГТ30ПЧ8	30,0	208±3%	83,5	7,0÷9,2	350÷460	0,85		15,0	38,0	1,26	18	/400	217	423	6	Δ*	КСВ-1	КВР-4			ВС-33А
СГС30Б	30,0	206±6%	83,5	4,2÷9,3	210÷466	0,8	26÷30	55,0	30,0	1,00	—	/400	182	422	6	Δ*	РН-600	КРЛ-26БМ			ЭС-30Б
СГС30-8	30,0	208±3%	83,5	5,5÷8,7	358÷580	0,85	26÷30	40,0	40,0	1,33	16	200/400	216	452	8	Δ*	РН-600	КВР-3-2			ВС-33А
ТГС30-8	30,0	208±3%	83,5	12,[illegible]±5%	400[illegible]±3%	0,8	26÷30	26,0	35,0	1,16	15	/400	206	472	4	Δ*	РН-600	КВР-3-2			ВС-33А
СГС40У	40,0	208	111	7,75÷8,35	387÷417	0,9	26÷30	29,0	39,0	0,97	5,5	/400	198	443	6	Δ*	РН-600	КВР-3-2			ВС-33А
ГТ40ПЧ8	40,0	208±2%	111	8,0±2%	400±2%***	0,8	Самовозбуждение 24		47,0	1,17	14	245/	257	430	6	Δ*	БРН-62	БРЧ-62;	БТТ-62;	БЗУ-62	—
СГС40П	40,0	208	111	7,5÷8,9	375÷445	0,8	26÷30	29,0	40,0	1,00	15	160/360	198	465	6	Δ*	РН-600	КВР-3-2			ВС-33А
ГТ60ПЧ8АТВ	60,0	208±2%	167	8,0±2%	400±2%**	0,8	Самовозбуждение 24		55,0	0,91	15		236	452	6	Δ*	БРН-62	БРЧ-62;	БТТ-62;	БЗУ-62	—
СГС90/360	75,0	330	120	7,5÷9,0	375÷450	0,9			62,0	0,83		300	233	550	6	Δ*	РН-600	КРЛ-33А			ВС-34

генератора

* Звезда с нулевым проводом.
** Загрузка нулевого провода не более 3% от номинальной мощности.
*** ±1% с системой точного регулирования частоты.

1. Generator type
2. Rated data
3. Power P_{rated} KvA
4. Voltage U, v
5. Current I, ampere
6. Speed n, rpm $\cdot 10^3$
7. Frequency cps
8. Excitation
9. Weight kg
10. G/P_{rated}, kg/KvA
11. Flight ceiling H km
12. Air consumption and pressure, dm^3/sec and mm H_2O.
13. Dimensions
14. Diameter, mm
15. Length, mm
16. Number of poles
17. Winding connection
18. Regulating equipment
19. Voltage regulators
20. Control and regulation boxes
21. Precision voltage regulation
22. Protection against over voltage
23. Outside resistance
24. Self-excitation

* Star with zero conductor

** Zero conductor load not more than 5% of rated generator power

*** ± 1% with precision frequency regulation system.

with respect to direction. As the regulated flow of energy we can use the mechanical energy, transformed into hydraulic or electrical energy, and also compressed air, taken from the aviation engines' compressor.

The general equations for the differential drive are

$$P = P_m \pm P_p;$$

$$n = n_m \pm n_p.$$

where P_m and n_m - are the power and rate of rotation at the input into the differential at the mechanical transmission shaft;

P_p and n_p - are the power and rate of rotation at the input into the differential on the regulating shaft;

P and n - are the power and rate of rotation at the generator's shaft.

The rationality of using one or another type of drive (whether simple or differential) depends on a number of factors: the range of the rotation rate, and the system of starting of the aviation engines, power and place of installation of the generators, electrical supply system and others.

In the technical specifications the drive is affected by: the type and forms of energy for rotating and regulating, the regulating principle, the main properties and technical data, types of control protection and signalization during normal and emergency working conditions.

MAIN PROPERTIES OF THE DRIVE

1. The power should be commensurable with the generator's capacity.

2. The overload capacity should correspond to the overload capacity of the generator.

3. The load characteristic should be descending, beginning with the value of the maximum permissible generator overload.

4. The transmission ratio should be subject to smooth regulation.

5. The drive should provide the distribution of the active capacity between generators working in parallel in proportion to their rated capacities.

MAIN TECHNICAL DATA

1. The drive should provide for a constancy of the rate of rotation during separate and parallel work of generators and all working conditions of the aircraft engines, beginning with low gas and ending with the take-off conditions.

2. Under all conditions, beginning with the low gas condition the drive should provide for drawing of power from the generator

100% - over a long period of time;
150% - during 5 min.;
200% - during 5 sec.;

3. The drive regulator should maintain a constant speed of rotation of the a-c generator with a precision of ± 2% without a corrector and not more than ± 1% with a corrector.

4. The length of the transition processes when the generator is turned on or when the rated load is dropped, is not more than 0.5-1.5 sec.

5. The efficiency should have its maximum value during the cruising conditions.

6. The control and regulation system should be calculated for a normal voltage of 27 v, should maintain its working capacity when it is connected for 16 v and should be maintained in the connected state during the 8 v voltage.

7. The weight should be not more than 0.7-12 kg/KvA without taking into account the additional weight of fuel and the cooling system.

8. The additional fuel consumption by the aviation engine should be not more than 0.1-0.2 kg/KvA/hour.

9. The flight weight should be not more than 2 kg/KvA.

PROTECTION AND SIGNALIZATION UNDER EMERGENCY CONDITIONS

1. Automatic disconnection of the drive, when the rate of rotation of the generator or regulator is higher or lower than the permissible speed.

2. Automatic device, excluding the possibility of transmission of the moment from the generator to the aircraft engine.

3. Automatic disconnection from the aircraft engines, when the drive of the generator is jammed.

4. Automatic signalization of the origination of dangerous conditions (excess of permissible temperatures, pressures, etc.).

2. Automatic Regulation of the Rate of Rotation of the Drive.

The automatic regulation of the rate of rotation of the drive provides the constant speed of the generator upon the change of the rate of rotation of the aircraft engine, the required drive power upon the change of the load of the generator, and uniform distribution of the active power between the generators operating in parallel. The regulation with respect to speed and power is carried out by the speed regulator, the sensitive element of which, reacts to the deviation of the rate of rotation or the frequency of the generator's current from the rated ones and by means of a servo mechanism, acts on the conditions of the drive's work. As the principal sensor of the regulator, we can use centrifugal pick-ups or tacho-generators.

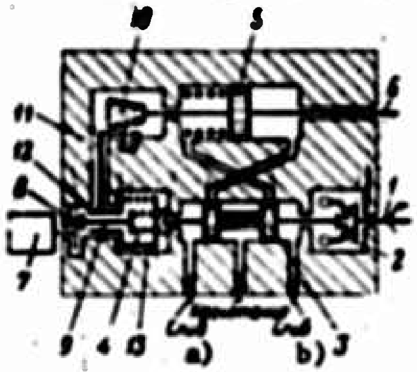

Fig. 2.1. Speed regulator with a correction electro mechanism: 1 - input shaft, 2 - centrifugal regulator, 3 - slide valve, 4 - spring of the corrector, 5 - servo piston, 6 - valve rod regulation, 7 - corrector, 8 - cam, 9 - corrector rod, 10 - cone, 11 - lever, 12 - sleeve, 13 - spring.
Key: A) delivery, B) discharge.

In fig. 2.1 we show one of the variations of the speed regulator the sensitive element of which is the centrifugal pick-up 2, rotated by the input shaft 1, at a speed proportional to the speed of the generator. The centrifugal force acting on the small weight, is transmitted to the slide-valve 3, pushing it to the left, and is balanced by springs 4 and 13. Oil is delivered under pressure into the cavity between the belts of the slide-valve 3 from the pumping stage of the oilpump. Let us examine the work of the regulator, using the example of the pneumatic-mechanical constant speed drive (CSD).

At the normal generator speed, slide-valve 3 is in the equilibrium position, closing with its belts the channels leading to both sides of the servo piston 5, connected kinematically with the regulating gate valve of the drive (6).

Upon the increase of the rate of revolution of the generator, due to the increase of the engine speed (speed regulation) or a decrease of the load (power regulation) the centrifugal regulator overcomes the stress of springs 4 and 13, displaces the slide-valve 3 to the left, delivering the oil pressure to the cavity to the right of the servo-piston 5, and connecting the left cavity with the discharge. The servo piston 5, moving to the left, closes the drive gate valve 6, decreasing the consumption of air through the turbine, as a result of which the rate of rotation of the generator decreases. The corresponding decrease of the centrifugal force of the small loads, causes the reverse movement of slide-valve 3 up to the restoration of the former state of equilibrium under the rated speed of the generator. Upon the decrease of the rate of rotation of the generator, the analogous process occurs in the reverse direction.

In order to assure the stability of the process of regulation, there is a rigid feed-back, made in the following way: On the rod of the servo piston 5, cone 10 is rigidly connected, to the generators, of which by means of a spring the pole of lever 11 is constantly pressed. The other arm of the lever is connected with sleeve 12, which presses on spring 13 of the feed-back, upon the movement of the servo cylinder 5, the pole of lever 11 slides along the cone. The lever turns, changing the stress on spring 13, and returns the slide valve 3 into the equilibrium position, i.e., into the regime of restoration of the equilibrium speed, but which is somewhat different from the initial speed, because the springs' stress has changed.

In order to eliminate the"static error", caused by the presence of feed-back, and for the parallel work of several generators, a correcting device is installed on the regulator, which is controlled by an electro-mechanism of corrector 7, which receive the signal from the residence circuits, reacting to the deviation of the frequency and the non-uniform distribution of active loads between the generators.

Electro-mechanism 7, receiving the electrical signal, slowly turns cam 8, which pushes rod 9, changing the stress on spring 4 of the corrector and restoring the prescribed speed of the generator.

During the parallel work of the generators, the process of regulation with respect to speed and their power, occurs in all the drives simultaneously. The uniform distribution of the active power between the generators and the precise regulation of their frequency is carried out by the correction device on signals from instruments measuring the frequency and active power (see the division on the parallel work of generators).

In fig. 2.2 we show the speed regulator with an electro-magnetic corrector. Let us examine its work, using the example of a hydraulic drive. The input shaft 1, is rotating with the speed proportional to the speed of rotation of the generator. The centrifugal weights 2, rotating with the shaft 1, move the load of slide-valve 3, overcoming the force of spring 4.

With the rated speed of the CSD, the forces of the centrifugal weights 2, are counterbalanced by the spring 4. Valve 3 is in the equilibrium position closing the gap leading to the servo cylinder 5. The latter retains in a certain position, the inclined washer of the hydraulic pump, which assures the constant speed of rotation. The rated speed is established by the corresponding stress of spring 4, by means of screw 8.

If the output speed of the CSD decreases from the point of equilibrium, the centrifugal forces of the weights become smaller than the force of the presssure of the spring and the slide-valve moves to the right, providing for the delivery of oil under pressure into the left cavity of the servo-mechanism, which in its turn, results in an increase of the angular deviation of the pump-washer, and increases the output velocity. In this case the increased centrifugal force of the loads will act again on the slide-valve, moving it to the left, until it will be counterbalanced by the force of the spring. This time the output opening leading to the servo-cylinder, is closed by the slide valve and the system occupies the position of equilibrium. If the output velocity of the CSD increases beyond the point of equilibrium of the force of the weights and the springs, the slide valve will move to the left, connecting the cavity of the servo-mechanism with the discharge. The servo-cylinder moves to the left, decreasing the angular deviation of the pump-washer and the output speed of the drive. The further regulation process is analogous.

The centrifugal weights are made of a magnetic hard material and may be attracted or repelled, decreasing or increasing the centrifugal force according to direction and value of the direct-current passing

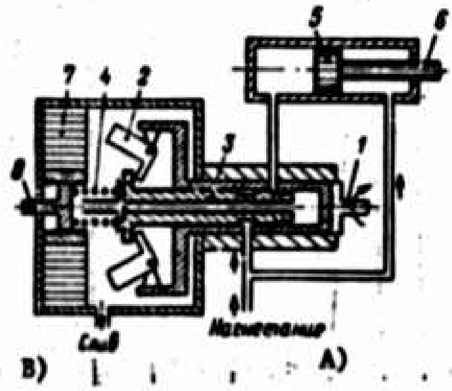

Fig. 2.2. Speed regulator with an electro-magnetic corrector: 1 - input shaft; 2 - centrifugal weight; 3 - slide valve; 4 - spring; 5 - servo-cylinder; 6 - rod of the regulating valve (washer); 7 - electro-magnetic corrector; 8 - regulating screw.
Key: A) delivery, B) discharge.

through electromagnet 7. The voltage on the electric magnet changes according to the signals of the active power measuring instrument, which acts in accordance with the deviation of the active load from the mean value.

From the diagrams examined we can see that the speed regulator controls the corresponding elements of the drive: in pneumatic systems the air delivery valve for the turbine; in hydraulic systems the incline of the washer, determining the output of the hydraulic pump; in mechanical by the angle at which the rollers are set up with respect to the toroids, determining the transmission ratio, in the electrical by changing the excitation.

3. Mechanical Constant Speed Drives.

The mechanical constant speed drive, receiving variable speed of rotation from the aviation engine, transform it into a constant speed at the output, by means of friction or fused variators. The power is transmitted by the force of friction between the rotating elements, which are held in contact with one another.

In fig. 2.3 we show certain typical structural diagrams of mechanical constant speed drives, the operating principles of which are analogous.

As an example let us examine a structural diagram of a friction mechanical drive shown in fig. 2.4. At the driving shaft 1, which is rotated by the aircraft engine, the driving disks 3, are fixed rigid-

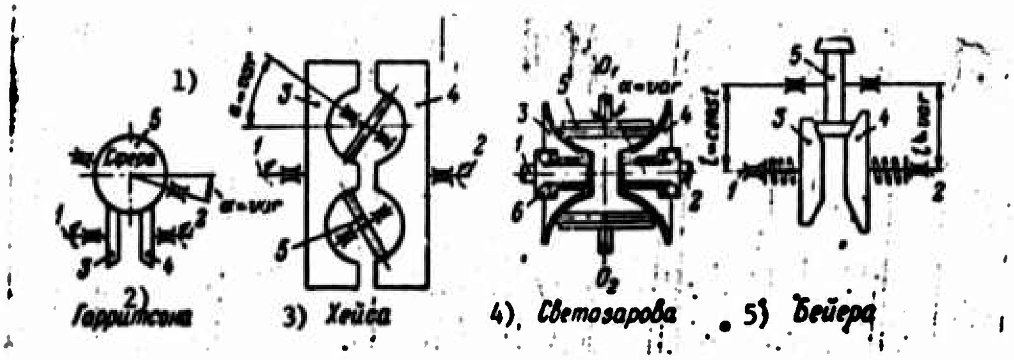

Fig. 2.3. Typical diagrams of frictional mechanical constant speed drives: 1 - input shaft; 2 - output shaft; 3 - driving disk; 4 - driven disk; 5 - roller; 6 - small sphere.
Key: 1. Sphere, 2. Harritson's, 3. Hay's, 4. Svegozarov's, 5. Bayer's.

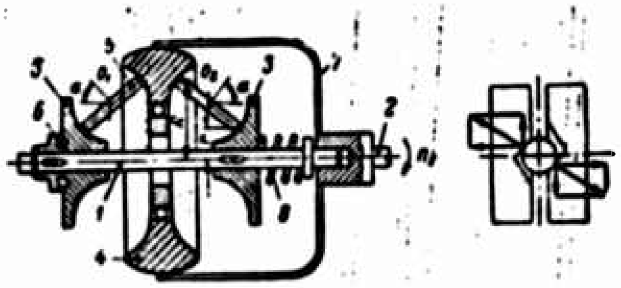

Fig. 2.4 Structural diagram of the frictional mechanical drive: 1 - input shaft; 2 - output shaft; 3 - driving disk; 4 - driven disk; 5 - roller; 6 - sphere; 7 - cup; 8 - spring.

ly. The driven disk 4, by means of cup 7, is connected with the shaft 2 of the generator. The working surfaces of disks 3 and 4 represent parts of the surface of torus and are interconnected with rollers 5. Three pairs of rollers are arranged symmetrically at an angle of 120° to one another. Their bilateral, symmetrical arrangement with respect to disk 4 removes axial stresses from its bearings. Spring 8 presses first the rollers 5 to disks 3 and 4. The driving shaft 1 is connected with the shaft of the aircraft engine, by means of a pole device, 6. Under the action of the torsion moment, the poles tend to roll along the sloping edges of the ditches (poles) as is shown in fig. 2.4, and move apart the washer and disk 3, automatically press rollers 5 to disks 3 and 4 with a force proportional to the moments transmitted.

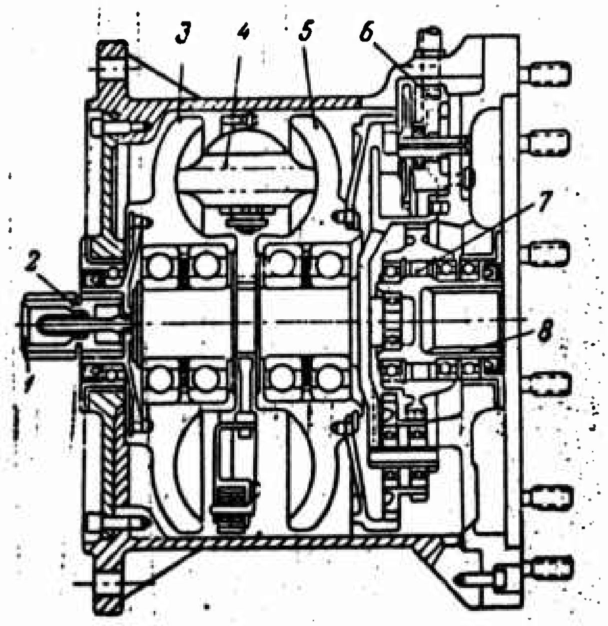

Fig. 2.5. Mechanical constant speed drive:
1 - shaft connected with the engines; 2 - cross-section of the shaft cut across upon the excess of the torsion moment; 3 - the driving toroid; 4 - roller; 5 - the driven toroid; 6 - oil pump; 7 - bypass sleeve; 8 - slits of the output shaft connected with the generator.

The rotation from the driving disk 3 is transmitted to the driven disk 4, by means of rollers 5. The ratio between the speed of rotation n of the driven disk 4 and n_m of the driven disk 3, is inversely proportional to the ratio between the radii of contact of the rollers to the corresponding disks:

$$\frac{n}{n_m} = \frac{r}{R}.$$

The reduction ratio varies smoothly by a turn of the axes of the rollers with respect to point O_1 and O_2, which change the contact radii of the rollers 5 with disks 3 and 4.

In fig. 2.5 we show the typical design of the mechanical drive in which the transmission ratio between the input and output elements is determined by the angle at which the roller is set up, with respect to the toroids.

The toroids are pressed to the rollers by the central load forming bolt. The contact stresses between the toroids and the rollers may reach 30,000 kg (force)/cm^2, which is possible only when high quality steel smelted under a vacuum is used. In the drive a special lubricant is used, which on the one hand assures a high friction coefficient, betweenthe other end toroids, and on the other, a good lubrication of the other parts.

In the mechanical drives the electronic regulation system is used, which increases the electrical signal of the deviation of the speed of revolution, and which acts on the electro-magnetic sleeve and servo motor. The latter set up the roller into a new position at an angle required for maintaining a constant rpm of the output shaft.

The mechanical drives provide for automatic maintenance of a constant speed at the output upon the change in the speed at the output in the range of 1:35, have a high efficiency η = 0.75 - 0.85, but are relatively heavy to regulate, since the transmission ratio during operation, which requires considerable efforts on the part of the several mechanisms and results in the increase of the time lag of the automatic regulation system. The drives are difficult to manufacture and their relative weight is 1.3 - 1.5 kg/KvA.

4. Simple Hydraulic Drive.

In the simple hydraulic drive, presented in fig. 2.6, the entire energy flow is regulated and transmitted in only one direction, from the primary motor (aircraft engine) to the generator. The efficiency of such a drive is about 0.75, its relative weight is 2-2.5 kg/KvA.

The drive includes a hydraulic pump, which transforms the mechanical energy of the aircraft engine into hydraulic energy, and the hydraulic motor, which transforms the hydraulic energy over the hydraulic pump into mechanical energy, which is delivered to the shaft of the synchronous generator. The drive requires absolutely hermetic conditions and the purity of the fluid, cooling of the fluid at high temperatures, and is difficult to start at low temperatures.

Rotor 1 of the hydraulic pump has several cylinders. Three are arranged along the periphery, the chambers of which upon the rotation of the rotor, communicate in sequence with the pipe lines through arch-shaped cavities of the stationary division disk 7 (see cross-section A-A).

When the rotor is rotated by the aircraft engine, distance 2 together with the supporting washer 6, are rolled over the non-rotating inclined washer 5, performing a reciprocal motion in cylinders 3, and passing through the left cavity of the dividing disk 7, under the action of spring 4, aspirate the oil from the low pressure line, and passing through the right cavity under pressure of the inclined washer 5, push out the oil through the high-pressure pipeline, space chambers of the hydraulic motors' rotor. If at the output of the hydraulic pump there is hydraulic resistance, a higher pressure is created here, in order to overcome this resistance.

The openings from the dividing disk 7 should be strictly oriented with respect to the axis of the inclined washer 5. At the places where the cavities of the disks are connected, the oil is cut off, i.e., the cylinder transports it from the aspirating region into the pressure region. The connections are located in the sector where the volume of the oil in the cylinder does not change when the piston passes over them.

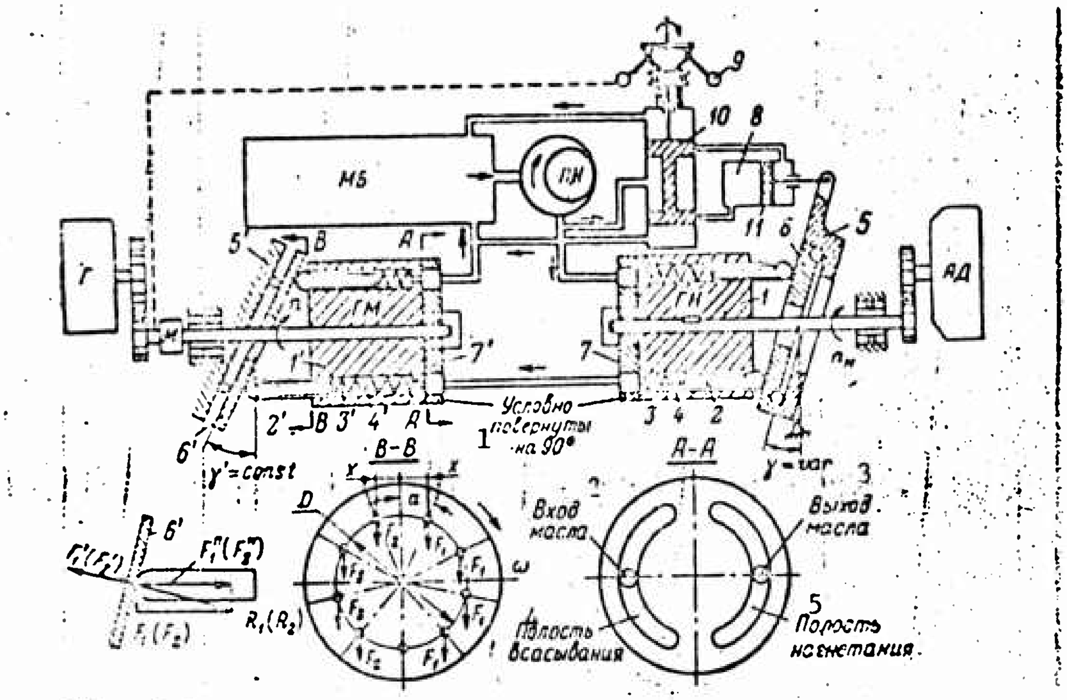

Fig. 2.6. Simplified diagram of a simple hydraulic drive: AE - aircraft engine; HP - hydraulic pump; HM - hydraulic motor; S - sleeve; G - generator; AP - auxiliary pump; OT - oil tank; 1, 1' - rotor; 2, 2' - piston; 3, 3' - cylinder; 4, 4' - spring; 5, 5' - inclined washer; 6,6' - support washer; 7,7' - dividing disks; 8 - servo mechanism; 9 - centrifugal regulators; 10 - regulator's slide valve; 11 - piston.
Key: 1. conventionally turned by 90°, 2. oil input, 3. oil outlet, 4. spiration cavity, 5. pressure cavity.

The piston cycle is determined by the position of the sloping washer 5, the angle of incline of which is set up automatically by the servo-mechanism on command of the speed regulator.

The output of the hydraulic pump, i.e., the volume of oil Q, delivered by the hydraulic pump per measure, is determined

$$Q = qmn_m = \frac{\pi d^2}{4} hmn_m = \frac{\pi d^2}{4} D \text{ tg } \gamma mn_m = An_m \text{ tg } \gamma \text{ cm}^3/\text{min},$$

where q - is the effective volume of 1 cylinder in cm^3;
m - is the number of pistons;
n_m - is the speed of the drive shaft;
d - is the diamter of the piston in cm;
h - is the cycle of piston in cm;
D - is the diameter of the circumference, over which the piston axes are located;
γ - is the angle of incline of washer 5 of the hydraulic pump;

$$A = \frac{\pi d^2}{4} DM.$$

The output of the pump may be changed by two ways: by changing the speed of rotation n_m of the rotor and changing the value of angle y of the inclined washer 5. In the first case we change the speed of the reciprocal motion of the pistons, and in the second we change the value of the piston cycle, i.e., the effective volume of the chambers. By changing the angle of incline of the washer, simultaneously with the change in the speed of rotation of the rotor, we can obtain a constant value of the pump's yield. This principle is the basis for obtaining a constant speed of rotation at the output of the hydraulic drive.

With a constant speed of rotation the output of the pump is regulated smoothly by changing the angle of incline of washer 5. If the washer occupies the perpendicular position to the axis of the pump, the pistons cannot form the reciprocal motion and there is no delivery of oil. If the washer is inclined into the inverse side, the oil delivery direction then changes.

The volume-rotor hydraulic machines possess the property of reversibility, i.e., they can be either pumps or motors. Because of this the design of the hydraulic motor in principle does not differ from the design of the pump, with the exception of the fixed washer 5', which has a constant angle of incline γ' to the axis of the motor. Consequently, the motor in one revolution consumes a constant amount of oil, i.e., it has a constant output.

The volume of oil consumed by the hydraulic motor permeate, is determined by the formula, analogous to the output of the pump:

$$Q_p = An_p \tan \gamma' \text{ cm}^3/\text{min},$$

where n_p - is the rate of rotation of the hydraulic motor;

γ'=const - is the angle of incline of washer 5' of the hydraulic motor.

$$Q_p = Q\ (1-S),$$

where S - is the oil leak in fractions of a unit (practically not more than 5%).

Substituting values Q_p and Q, after transformation we obtain

$$n_p = \frac{1 - S}{\tan \gamma'}, n_m \tan \gamma = Kn_m \tan \gamma.$$

In this way, the rate of revolutions of the hydraulic motor is proportional to the tangent of the angle of incline of the pump's washer 5.

In fig. 2.6 we show a diagram of distribution of forces in the points of contacts between the pistons of the hydraulic motor and the inclined washer 5', resulting from the pressure of the fluid on the pistons.

Into the chambers of the cylinders, which are in the compression zone of the dividing disk 7' (see cross-section B-B), the fluid is delivered under high pressure p_1, and into the chambers which are in the discharge zone, under a low pressure p_2. Under the action of these pressures, perpendicularly to their plane in the points of contact of each piston, against the inclined washer 5', the following forces are active: F_1' - in the delivery is on and F_2' - in the discharge zone:

$$F_1' = \frac{\pi d^2}{4} \frac{p_1}{\cos \gamma'} \quad \text{and} \quad F_1' = \frac{\pi d^2}{4} \frac{p_2}{\cos \gamma'}$$

Accordingly, at these points the inclined washer acts on the pistons by the forces of the reaction R_1 and R_2, directed against forces F_1'

and F'_2. The forces R_1 and R_2 are decomposed into two components: the longitudinal F''_1 and F''_2, which act along the axis of the pistons, and forces F_1 and F_2 perpendicular to them, which create the rotating moment of the rotor:

$$F_1 = R_1 \sin \gamma' = \frac{\pi d^2}{4} p_1 \tan \gamma';$$

$$F_2 = R_2 \sin \gamma' = \frac{\pi d^2}{4} p_2 \tan \gamma'.$$

Forces F_1 and F_2 act on the arms, the lengths of which depend on the position of the pistons with respect to the inclined washer 5'. The lengths of the arms are determined (see view B-B) as:

$$X = \frac{D}{2} \sin a.$$

If we disregard value p_2 of the counterpressure (which is usually many times less than the pressure on the input), then the moment with respect to the axis of rotation of the rotor from one piston on the high pressure side, will be

$$M_1 = p_1 \frac{\pi d^2}{4} \frac{D}{2} \tan \gamma' \sin a.$$

This moment changes according to the sinusoidal law depending on the angle of turn of the rotor, i.e., it pulses from 0 when a equals 0 to M_{max} when $a = \frac{\pi}{2}$.

The total moment of all the m of the pistons, which are on the side of the high pressure, is equal to

$$M = \sum M_1 = p_1 \frac{\pi d^2}{8} D \tan \gamma' \left| \sin a + \sin \left(a + \frac{2\pi}{m}\right) + \sin \left(a + \frac{4\pi}{m}\right) .. \right]$$

The total moment is also non-constant, but changes with the periods of oscillations, equal to $\frac{2\pi}{m}$. The irregularity of the moment decreases with the increase of the number of pistons. In this case their uneven number yields a smaller pulsation than the greater even one. This is explained by the fact that when the piston passes through the cut-off line, only one piston does not participate in the work when there is an uneven number of them.

SPEED REGULATION. During a nominal speed of revolution of the generator the centrifugal regulator 9 by means of slide valve 10, covers both channels of the servo-mechanism 8, fixing the cylinder 11 and inclined washer 5, into a specific position.

Upon the increase of the rate of revolution of the aircraft engine the output of the pump increases, the speeds of the hydraulic motor and the generator connected with it, increase proportionally. This deviation of the speed of the generator from the rated speed is perceived by the centrifugal regulator line, which moves slide-valve 10 upwards. The fluid from the pressure line is delivered to the right cavity of the servo-mechanism 8; piston 11 moves to the left, decreasing the angle of incline of washer 5 of the pump; the output of the pump in this case decreases, returning to the rated yield, and accordingly the rate of revolution of the hydraulic motor and generator decreases to the rated value. At the centrifugal regulator 9, slide-valve 10 returns into the initial position. The slide-valve covers both channels of servo-mechanism 8, fixing a new position of piston 11 and inclined washer 5, corresponding to the new speed of the aircraft engine. Upon a decrease of rate of revolution of the aircraft engine, the process of regulation of the hydraulic drive continues in the same sequence, only regulator 9, slide-valve 10, piston 11 and inclined washer 5 move into the opposite direction.

POWER REGULATION. Upon the decrease of the load in the generator's system, the moment on the shaft of the hydraulic motor decreases. This causes an increase in the rate of revolution of the hydraulic motor and generator. The centrifugal sensor 9 reacts to the increase of the speed and relates the drive as it did upon the increase of the rate of revolution of the aircraft engine.

Upon the increase of the load the process of regulation occurs analogously with the decrease of rate of revolution of the aviation engine.

5. Hydro-Mechanical Drive with a Hydraulic Differential (Type 1).

The hydro-mechanical drive with a hydraulic differential transmits energy from the aircraft engine to the generator in two currents: mechanical, which is uncontrolled, and hydraulic which is controlled.

In the mechanical transmission of the flow of energy the fluid is used as a rigid link, providing a mechanical connection between the aircraft engine shaft and the generator shaft.

The hydraulic flow of energy is controlled and transmitted by the hydraulic differential, upon which insufficient mechanical energy (at low rates of revolution) delivers additional energy to the generator shaft by the hydraulic way, and during an excess of mechanical energy removes it hydraulicly from the shaft of the generator back to the aviation engine shaft, as shown in fig. 2.7.

The hydro-mechanical drive in connection with the common drive has a lower weight, size, and a higher efficiency (up to 0.85).

The simplified diagram of the hydro-mechanical drive with a hydraulic differential is given in fig. 2.8. The drive consists of: a hydraulic pump, HP; a hydraulic motor, HM; and a system of automatic revolution, the operating principle of which is analogous to the one discussed in § 2 and 4. Let us note certain specific features:

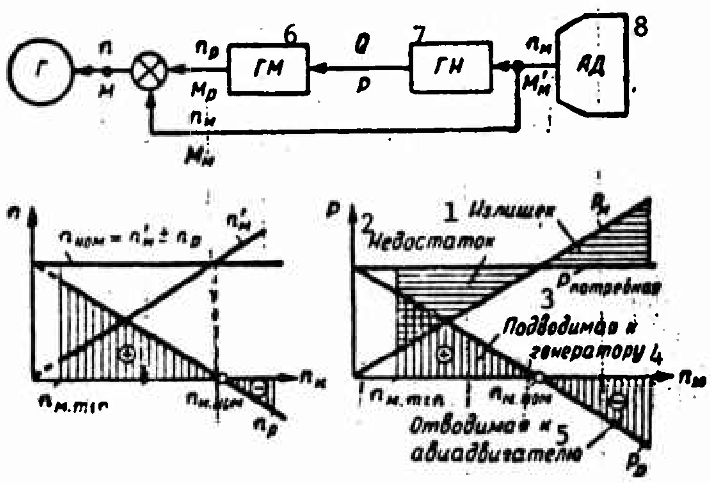

Fig. 2.7. Structural diagram and curves of the rates of revolution and power of the differential hydraulic drive.
Key: 1. Excess, 2. shortage, 3. required, 4. delivered to the generator, 5. taken off, to the aircraft engine, 6. hydraulic motor (HM), 7. hydraulic pump (HP), 8. aircraft engine (AE).

Rotors 1 of the pump and 1' of the motor are rigidly connected with one another and rotate as a single entity (drum) out of the drive shaft of the aircraft engine with a variable number of revolutions n_m. The inclined washer 5 of the pump is connected to its servomechanism 8, of the regulating system and the change is positioned by angle γ in both directions from 0. Finally, washer 5' of the hydraulic motor has an invariable angle of incline γ' and rotates the constant speed.

The separating disk 7' is rigidly connected with washer 5' and rotates synchronously with it, while the arched cavities are strictly oriented with respect to the plane of the washer.

In the rated operating conditions washer 5 of the pump is set up on a 0 angle ($\gamma = 0$), more precisely by the angle which provides a compensation for leaks in the pump, and the hydraulic motor, and for maintaining the required pressure in the hydraulic system. In this case pistons 2 have no axial movement. The fluid does not circulate between pistons 2 and 2', but forms a hydraulic lock. Pistons 2' are thus rigidly connected with washer 5' and are unable to turn with respect to it. Due to the rigid connection, caused by the hydraulic lock, the entire power transmitted from the aircraft engine to the generator is determined only mechanically, while its rate of revolution is determined by the rate of revolution of the aircraft engine, i.e., without taking into account the mechanical reducing gear of the hydraulic drive n_m. A certain slipping through ($n < n_m$) is possible by means of leaks.

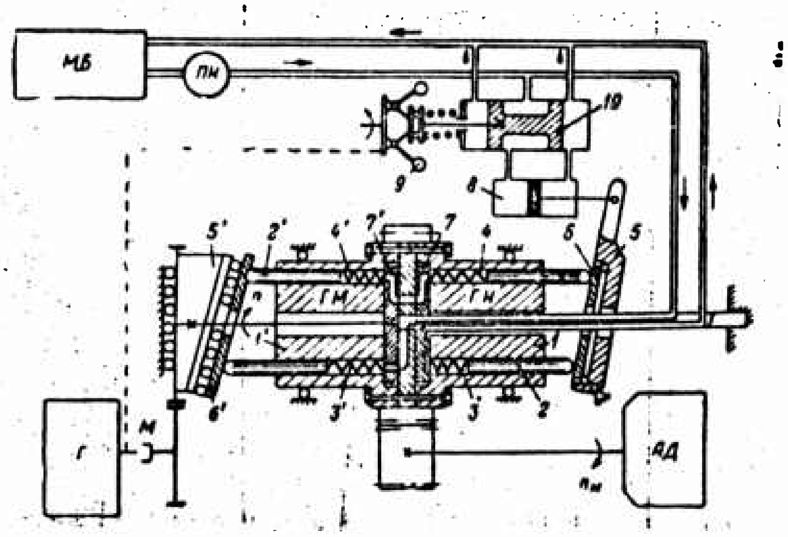

Fig. 2.8. Simplified diagram of the hydro-mechanical drive with a hydraulic differential: AE - aircraft engine; HP - hydraulic pump; HM - hydraulic motor; S - sleeve; G - generator; AP - auxiliary pump; OT - oil tank; 1,1' - rotors; 2,2' - pistons; 3,3' - cylinders; 4,4' - springs; 5,5' - inclined washers; 6, 6' - supporting washers; 7,7' - dividing disks; 8 - servomechanism; 9 - centrifugal regulator; 10 - slide-valve of the regulator.

If the speed of the aircraft engine with respect to the speed of the output shaft decreased ($n_m < n$), then washer 5 will be deflected into the positive direction by the automatic system. When the drum is rotated, the cylinders 2, together with the supporting bearing 6, roll about the inclined washer 5, performing a reciprocal motion, and pump the fluid into the hydraulic motor cylinders. The hydraulic motor, rotating in the common drum, converts the reciprocal motion of the pistons into the rotating motion of the inclined washer 5'. The rate of revolution of this washer without taking the leaks into account, is determined as

$$n_p = n_m \frac{\tan \gamma}{\tan \gamma'}$$

In this way, the rate of revolution of washer 5', obtained by the hydraulic weight, is directly proportional to the speed of the pump and the ratio between the tangent of the angle of incline of washer 5 of the pump to the tangent of the angle of incline of washer 5' of the hydraulic engine.

Since the body of the pump and the hydraulic motor are representing a single entity, the rate of revolution of the output valve of the drive (inclined washer 5') is determined by the sum of two speeds: speed of rotation of the body of the pump and the speed of slipping of washer 5' with respect to washer 6', due to the reciprocal motion of the pistons:

$$n = n_m + n_m \frac{\tan \gamma}{\tan \gamma'} = n_m \left(1 + \frac{\tan \gamma}{\tan \gamma'}\right) = \text{const.}$$

If the speed of the aircraft engine has increased with respect to the speed of the output shaft ($n_m > n$), then washer 5 is deviated in the negative direction by the automatic system. The pump and hydraulic motor change places. Thanks to this, washer 5' begins to be impeded, and its total rate of revolution attains a constant value.

$$n = n_m - n_m \frac{\tan \gamma}{\tan \gamma'} = n_m \left(1 - \frac{\tan \gamma}{\tan \gamma'}\right) = \text{const.}$$

In this case on rotor 1 - 1' there is an excess of power, which by means of pistons 2' is removed into the fluid and from the fluid through pistons 2 is returned on the aircraft engine's shaft.

In this type of drive the power from the aircraft engine is transmitted to the generator in two ways: mechanical, directly through the rotor and the cylinders of the hydraulic motor onto washer 5'; and hydraulic, through the pump into the fluid and then from the fluid through the hydraulic motor pistons to the same washer 5' on to the driven shaft

$$P = \frac{1}{\eta_e} P_e = P_m + P_p,$$

where P_e - is the electro-magnetic power of the generator;

P_m - is the mechanical power component;

P_p - is the hydraulic power component.

The mechanical power does not change its direction, while its value depends only on the value of the load (pressure p) and the value of the rate of revolution of the aircraft engine, and is transmitted through the body and the pistons of the hydraulic motor HM, onto washer 5'

$$P_m = \eta_m C_H p n_m \text{ [kw]},$$

where η_m - is the mechanical efficiency of the hydraulic drive;

C_H - is the proportional coefficient.

The hydraulic power may change its sign, depending on the value of the mechanical power, coming from the aircraft engine and is determined as

$$P_p = \frac{\eta_m}{612} Qp \text{ [kw]}.$$

Let us examine as an example the hydro-mechanical drive of the Sandstrand company, the design and diagram of the control of which are given in figures 2.9 and 2.10.

The pump in the motor of the axial multi-plunger type, are arranged in a single body, are rigidly interconnected and powered by the aircraft engine's shaft. Their rotors have several cylinders located along the periphery.

The plungers of the pump move in the cylinders as a result of pressure of the regulated inclined washer 4 on them. The stroke of the plungers varies between two maximums (passing through a 0) in relation to the angle at which the washer is set. The inclined washer 11 of the hydraulic motor has a constant angle of incline and is usually connected with the generator's shaft.

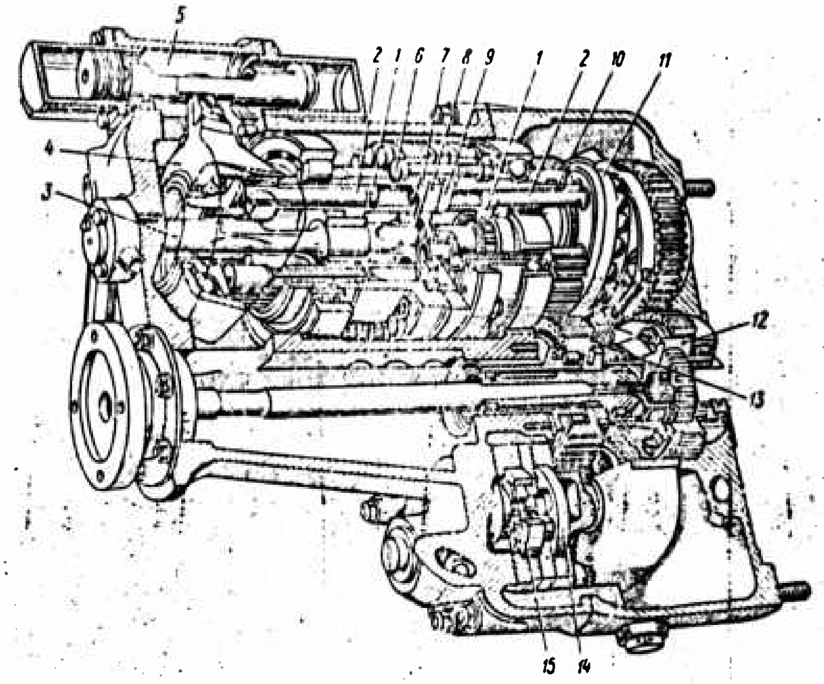

Fig. 2.9. Design of the hydro-mechanical drive with a hydraulic differential, made by the Sandstrand Company:
1, 2 - plungers of the regulated and non-regulated rotors; 3 - shaft of the regulated rotor; 4 - regulated, inclined washer; 5 - servo-pistons; 6 - regulated rotors; 7 - stationary distributing disk; 8 - feed washer; 9 - rotating dividing disk; 10 - non-regulated rotor; 11 - non-regulated inclined washer; 12, 13 - output and input gear; 14 - auxiliary pump; 15 - exhaust pump.

Between the two sets of plungers are two distributing disks 7 and 9, which distribute the oil between the pump and the motor. Disk 7 is installed on a stationary axis, and disk 9 is installed on an eccentric journal of the output shaft. Between the distributing disks 7 and 9, a feed washer 8 is installed which has bypass windows and is rigidly connected with the rotor.

When the rotor unit is revolving, the position of the inclined washer 4 of the hydraulic pump is set up by the regulator, depending on the conditions of its tune-up. In accordance with the difference between the speeds of the input and output shaft, the required amount of oil is delivered to the hydraulic motor plungers under high pressure. As a result of this, the plungers through the axial pressure force component, transmit the full rate of revolution of the hydraulic motor to washer 11, and through the pressure force component, perpendicular to the axis of the rotor, create a rotating moment on

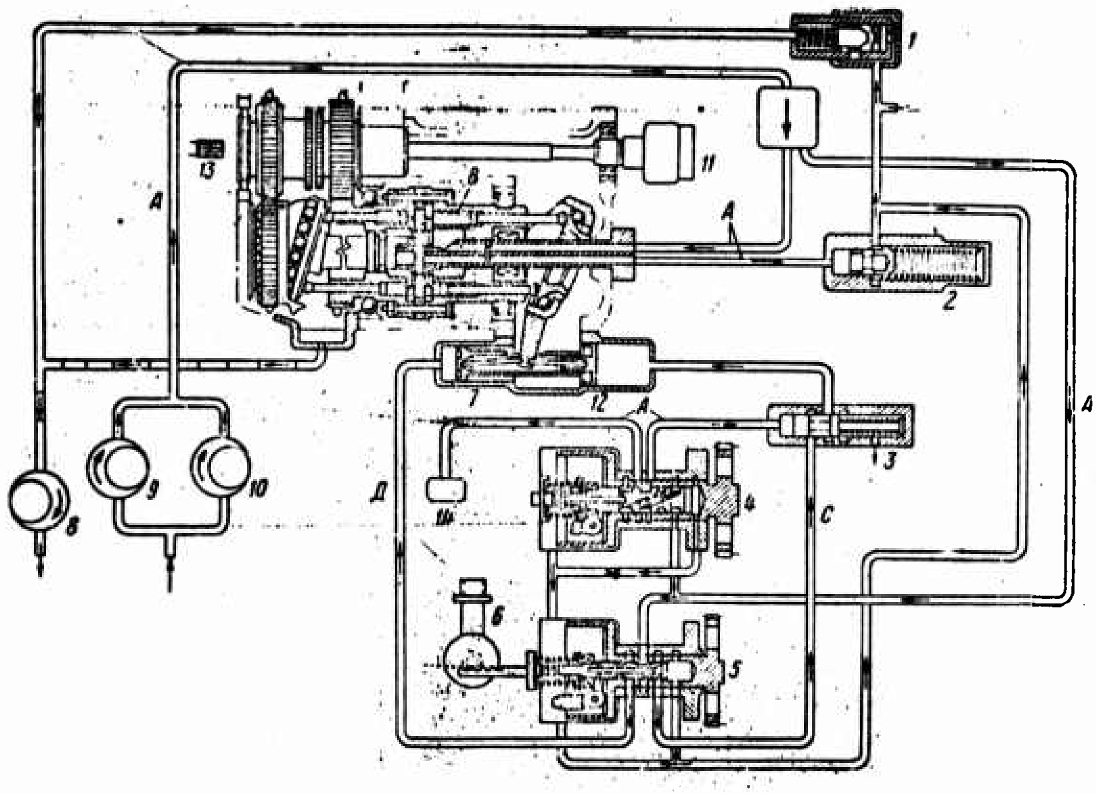

Fig. 2.10. The general diagram of the hydro-mechanical drive control built by the Sandstrand Company:
A- pressure at the inlet; B - operating pressure; C - pressure for regulation during a high speed of the engine; D - pressure for regulation during a low speed of the engine;
1 - bypass route; 2 - safety valve at the input; 3 - bypass valve (for oil) for a higher number of rpm; 4 - regulator of the increase of the number of rpm; 5 - main regulators; 6 - electric motor for frequency correction; 7 - cylinder of the lower limit of the number of rpm regulator; 8 - evacuating pump; 9 and 10 - auxiliary oilpumps; 11 - tail of the input shaft; 12 - cylinder of the upper limit of the number of rpm regulator; 13 - generator shaft; 14 - switch for turning off the pressure.

washer 11, which increases the rate of revolution of the output shaft.

The regulation system is built in such a way, that as long as the number of rpm at the output does not reach 6000 rpm, washer 4 of the hydraulic pump remains in the position of the complete cycle of the plungers, during which an increased delivery of oil assures the increase of the number of revolutions at the output in comparison with the number of revolutions at the input.

When the prescribed number of revolutions at the output is reached, the system is in the state of equilibrium until the number of revolutions at the input increases. In this case the speed regulator will decrease the angle of the inclined washer 4 of the hydraulic pump and in this way will decrease its output. This will result in establishing the prescribed rate of revolution at the output.

When the number of revolutions at the input is equal to the required number of revolutions at the output, inclined washer 4 of the hydraulic pump will occupy a neutral position (if one does not take the oil leaks into account), the plungers cannot perform the reciprocal motion, a hydraulic lock is formed and the system operates as a rigid drive. In this case the power from the aircraft engine is transmitted to the generator only by the mechanical way with a high efficiency. The calculated regime is selected from the condition of its maximum length during the flight.

The further increase of the rate of revolution at the output, causes the reverse turn of the inclined washer 4 of the hydraulic pump, so that the hydraulic motor begins to operate as a hydraulic pump, while the hydraulic pump digs up the excess oil and delivers it in the opposite direction, i. e., to the additional supply cavity. Because of this, the washer 11 slips into the opposite direction and the speed of the generator is restored to the rated speed.

The system of regulation maintains the prescribed rate of revolution of the generator and the uniform distribution of the load between the generators connected in parallel and consists of the main regulator, electric motor with a precision frequency regulation, frequency regulator and their generator load equalizer.

The action of this system provides a precision setting of the inclined washer 4 of the hydraulic pump by means of simple mechanism, and accordingly the prescribed rate of revolution of the generator.

The main regulator consists of a hydraulic slide-valve controlled by a centrifugal pick-up and electric motor-corrector. The slide-valve regulates delivery of oil to the servo-mechanism. The regulator sleeve is connected with a generator drive shaft. Small weights are installed on the sleeve, the levers of which act on a two-built slide valve, which is pressed by two springs. The main spring provides the preliminary stress, while the strain of the lesser spring regulates the electric motor of the frequency regulator.

When the rate of revolution of the aircraft engine or the load on the generator changes, the slide-valve of the regulator will move in one direction or another, and will communicate the high pressure oil cavity with the corresponding cavity of the servo-mechanism. With the settled, prescribed rate of revolution, the slide-valve occupies a neutral position and covers the main lines which lead to the servo-mechanism for setting up washer 4, which locks the inclined washer 4 into a specific position.

The load is distributed between generators connected in parallel and the drives automatically by means of straining the smaller spring of the main regulator, connected with the drive. The spring is strained by the gear of the electric motor, which receives a signal through a magnetic amplifier from the current transformers, which are installed in the generator's circuit.

The second centrifugal generator connected with the output shaft, reacting on the increase or decrease of the rate of revolution above the permissible limits, gives out a hydraulic signal to the pressure switch and to the distributing valve which drains the oil, which goes from the main regulator to the servo-mechanism.

The electrical contact of the pressure switch is intended for connection with the corresponding relay in the aircraft system, in order that the a-c generator would remain under a load, when the constant speed drive has a higher or lower output speed.

The reserve of oil for the cylinder unit and the regulating operations is provided by two built-in pumps, one of which is put into operation by the input shaft, and the other by the output shaft. This assures a reliable contact of the plungers with the inclined washers. An oil-evacuating pump is also provided for, which is powered by the output shaft.

The hydraulic drive is connected with the generator by a bypass sleeve of the spring-type, which transmits the rotating moment only in the direction from the aircraft engine to the generator and excludes in this way the work of the latter in the system of the engine.

The lubrication of the hydraulic drive is provided by drawing some oil from the feed system. The system includes an oil tank, heat transfer changer, and a metal 33-micron filter.

6. Hydromechanical Drive with Hydraulic Differential (Type 2).

In the hydromechanical drive with a hydraulic differential of the second type, the rotor, combined with the shaft of the aircraft engine, has a constant effective volume, and the rate of revolution of the generator is regulated through the regulated volume of the chambers of the second rotor. The block diagram of this drive is given in fig. 2.11.

Rotor 2, connected with shaft 1 of the aircraft engine has radial chambers in which pole-plunger 3 can move. The rotor with poles is encompassed by a manular clamp 4, which has an eccentricity with respect to the axis of rotor 2. Clamp 4 is made together with the output shafts 6 and second rotor 7, which have radial chambers with pole plunger 8.

Upon rotation of rotor 2, with respect to clamp 4, poles 3 perform a reciprocal motion, as a result of which the fluid from the low pressure cavity is pumped into the high pressure cavity, both over the separating channels of shaft 6 and the stationary dividing sleeve 5, enters the chambers of rotor 7.

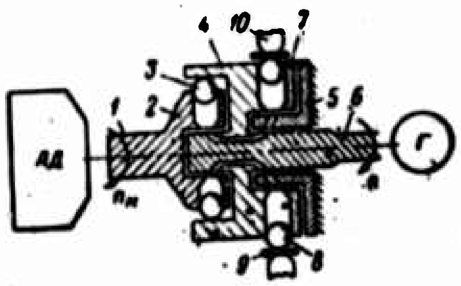

Fig. 2.11. Block-diagram of the hydromechanical drive with hydraulic differential: AE - aircraft engine, G - generator, 1 - drive shaft, 2 - "unregulated" rotor, 3 - pole plungers, 4 - angular clamp, 5 - separating sleeve, 6 - output shaft, 7 - regulated rotor, 8 - pole plungers, 9 - regulated manular clamp, 10 - controlling servo piston.

The regulated clamp 9 by means of a servo-piston 10, is installed with an eccentricity with respect to shaft 6. Upon the increase of the rate of revolution of the aircraft engine, clamp 9 is used for a smaller eccentricity, as a result of which plungers 8 provide a smaller effective volume of the rotor chamber. The rate of revolution of rotor

7 and together with the clamp 4, with respect to shaft 1 and rotor 2, decrease while it maintains a constant absolute rate of revolution of the generator.

With the rate of revolution of rotor 2, equal to the rated rate of revolution of the generator, the regulator eliminates the eccentricity of clamp 9, as a result of which plungers 8 cannot make their advancing motion any more. Between plungers 3 and 8 a hydraulic log forms; the shaft 6 through clamp 4, plungers 3 and rotor 2, are rigidly connected with the shaft 1 of the aircraft engine.

Upon the further increase of the rate of revolution of the aircraft engine the eccentricity of clamp 9 becomes negative, which turns rotor 7 into a pump and rotor 2 into a hydraulic motor. The hydraulic log is removed and the fluid is pumped into the opposite direction, rotor 2 overtakes and passes clamp 4.

Let us examine as an example the hydromechanical drive of the General Electric Company.

The drive consists of hydraulic pump with variable output connected with the aircraft engine shaft, and the hydraulic motor connected by means of spherical pistons with the synchronous generator's shaft. The hydraulic pump and hydraulic motor are located in a single body, as is shown in fig. 2.12.

The hydraulic pump consists of a stationary external body and rotor 1 inside of it, with seven radially arranged cylinder channels, each of which contains a spherical plunger 2. Between the stationary body and the rotor lies a ring free, which rests with its external surface on pistons 4 and 5, which can move in the body's cylinders in the radial direction under the effect of the regulation system. The movement of these pistons causes displacement of the ring and change in its eccentricity with respect to the axis of rotation of the rotor. The spherical plungers of the rotor, supported on the external surface of the ring, because of its eccentricity move into the radial direction, proportionally to the value of the eccentricity. The spherical plungers during the displacement press out the oil into the channel of the hollow shaft, from which it arrives into seven radially arranged cylindrical channels of the hydraulic motor with a spherical plunger 2'. When the eccentricity is equal to 0, the spherical plungers are addressed and the oil is not pumped in.

The rotor of hydraulic motor 1' is located inside the rotor of the hydraulic pump. The spherical plungers 2' of the hydraulic motor rotor rest on the internal elliptical surface of the rotor of the hydraulic pump. Under the action of the pressure of the oil arriving from the channel of the hollow shaft, the hydraulic motor plungers move into the radial direction, and resting on the rotating elliptical surface

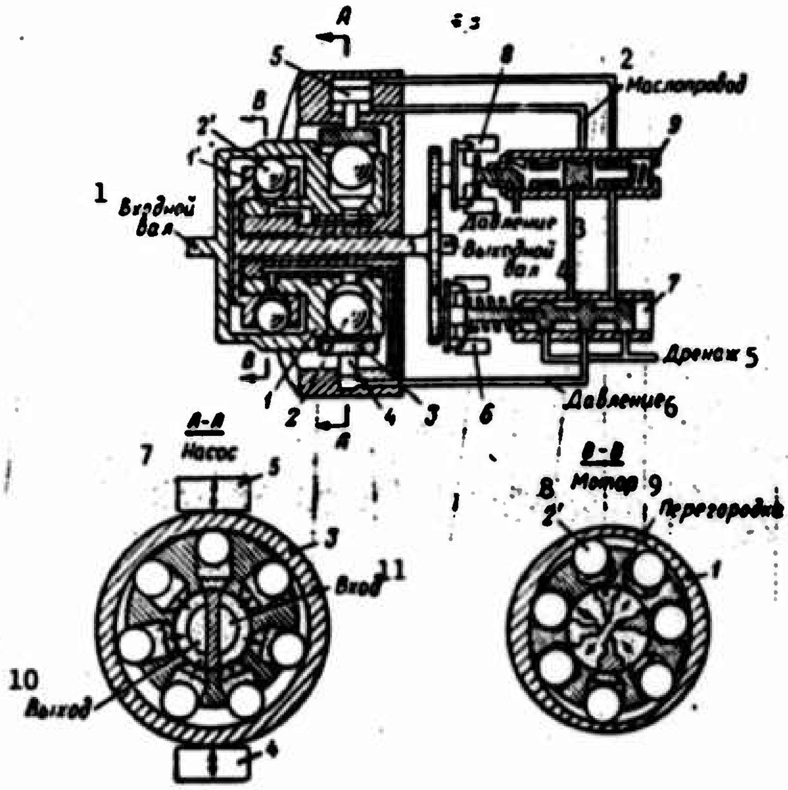

Fig. 2.12. Hydromechanical drive of the General Electric Company: 1,1' - rotors; 2,2' - plungers; 3 - ring; 4 - reverse piston; 5 - direct piston; 6 - centrifugal regulators; 7 - slide valve; 8 - speed excess regulator; 9 - slide valve.
Key: 1. input shaft, 2. oil conduit, 3. pressure, 4. output shaft, 5. drainage, 6. pressure, 7. pump, 8. motor, 9. partition, 10. outlet, 11. inlet.

of the hydraulic pump rotor, put into a rotating motion the hydraulic motor's rotor.

The system of connection of the oil conducting channels is built in such a way that the regulating system, change the value in the direction of the oil pressure, assures the slipping or completion of revolution of the hydraulic motor's rotor with respect to the hydraulic pump's rotor and maintain the constancy of the rate of revolution of the output shaft.

When the pump cylinder unit rotates with the speed of the aircraft engine, the hydraulic motor cylinder unit will have a velocity (greater or smaller) depending on the position of the pistons, with regulate the eccentricity of the pumping unit in the body.

The drive is built in two variations: the first for 20 KvA (30 hp weighing 15.8 kg) provides a constant speed of the output shaft of 8000 rpm the speed of the aircraft engine varying from 4000 to 8300 rpm and the second for 40 KvA (60 hp weighing 22.7 kg) provides a constant speed of the output shaft amounting to 6000 rpm, the aircraft engine speed varying between 4000 and 8300 rpm.

The a-c frequency regulation precision amounts to $\pm$ 1% and may by brought up by means of an electrical corrector to $\pm$ 0.25%.

7. Fluid Drive with a Planetary Differential.

The measured part of the power with such a drive is transmitted from the aircraft engine to the generator by the mechanical planetary gear with a high efficiency, and the hydraulic transmission is used to transmit only certain parts of the full power in one direction or another.

In the calculated operating conditions of the drive during the aircraft engine speed-off $n_{calc} = n_{m.mean} = \frac{n_m + n_{m\ min}}{2}$, which corresponds to the cruising flight conditions, the entire power is transmitted by the purely mechanical means through the planetary gear and the hydraulic drive in this case is practically idle.

It is possible to have a series or different combinations of the differential mechanisms with a hydraulic transmission, however, they can be reduced to the two principal layout systems:

Inclusions of a hydraulic drive between the driving end of auxiliary shafts, i.e., branching of the power on the driving shaft;

Inclusion of the hydraulic transmission between the auxiliary and the driven shafts, i.e., branching of the power on the driven shaft.

The hydraulic machine is connected with the driving end of the driven shaft, is non-reversive, but should be regulative. The hydraulic machine, connected to the differential mechanism DM, in the general case is reversible and may be non-regulative.

Each of these hydraulic machines, depending on the rate of revolution of the aircraft engine, may operate alternately either as a pump or as a hydraulic motor.

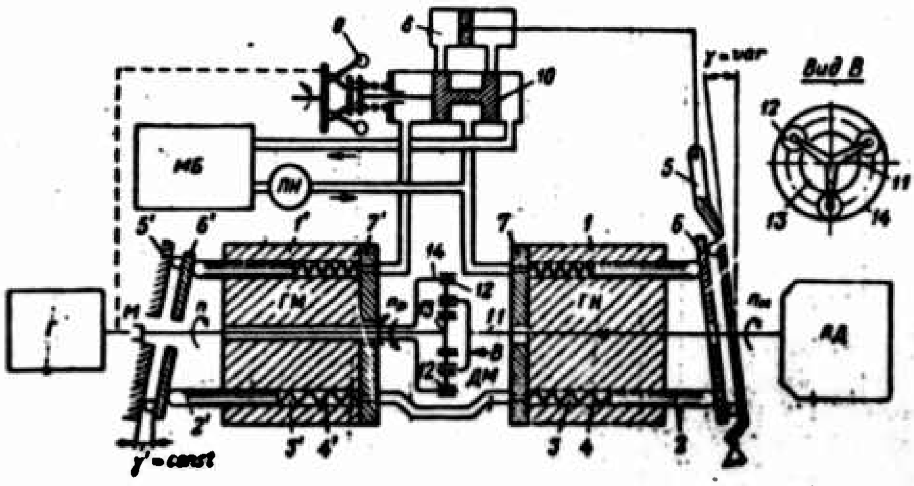

Fig. 2.13. Simplified diagram of the fluid drive with a planetary differential: AE - aircraft engine; HP - hydraulic pump; HM - hydraulic motor; S - sleeve; G - generator; AP - auxiliary pump; OT - oil tank; DM - differential mechanism; 1,1' - rotor; 2,2' - piston; 3,3' - cylinder; 4,4' - spring; 5,5' - inclined washer; 6,6' - thrust rings; 7,7' - separating disks; 8 - servo mechanism; 9 - centrifugal generator; 10 - slide valve of the regulator; 11 - planet pinion pole; 12 - planet pinions: 13 - sun gear; 14 - crown pinion.

A number of various combinations of the planetary reducing gear in a fluid drive is possible. However, the operating principle of the fluid drive remains the same as in the examined instance of the fluid drive with the hydraulic differential.

One of the simplified diagrams of the fluid drive with a planetary differential is given in fig. 2.13. The drive consists of: a hydraulic pump HP, hydraulic motor HM, differential mechanism DM, and a system of automatic regulation, the operating principles of which are analogous of that examined above. Let us note certain specific features.

The rotor 1 of the pump and pole 11 of the satellite pinions are rotated by the drive shaft of the aircraft engine with a variable speed a_m. The regulated washer 5 of the pump is connected with servo mechanism 8 of the regulation system and can change its position by angle γ into both directions from 0. The nonregulated washer 5' of the hydraulic motor have an invariable angle of incline γ'. The crown pinion 14 is rigidly connected with rotor 1' of the hydraulic motor. The sun gear 13 is rigidly connected with the generator's shaft. The dividing disks 7 and 7' are stationary and their arched hollows are strictly oriented with respect to the planes of the corresponding washers 5 and 5'.

Under the calculated regime washer 5 of the pump is set up for a 0 angle ($\gamma = 0$), more precisely at an angle, assuring the compensation for the leaks in the pump, hydraulic motor, and for maintaining the required pressure in the hydraulic system. In this case the cylinders 2 do not have an axial movement. The fluid is not circulating between pistons 2 and 2' but forms a hydraulic log. Pistons 2' are rigidly connected with washers 5' and may turn with respect to fluid. Consequently, rotor 1' of the hydraulic motor together with the crown pinion 14, are stationary. As a result, the entire power from the aircraft engine to the generator is transmitted by only the mechanical weight, and its rate of revolution is determined by the rate of revolution of the aircraft engine and mechanical reducing gear of the hydraulic drive, i.e, $n = n'_m$,

where n - is the rate of revolution of the output shaft of the drive;

n'_m - is the rate of revolution of the aircraft engine, taking into account the gear ratio of the reducing gear.

If the speed of the aircraft engine decreases ($n'_m < n$), then disk 5 inclines automatically towards the pumping operation of the hydraulic pump. The pistons 2, on the thrust-bearing 6, are rolled about on the inclined disk 5, performing a reciprocal motion, and pump fluid into the cylinders of the hydraulic motor HM. Pistons 2' transmit the pressure to the stationary inclined disk 5', the reactions of which act upon the entire body of the hydraulic motor, forming two force-components (see paragraph 4), one of which creates the rotating moment, which through the crown pinion 14 produces an additional rate of revolution of satellite pinions 12. The additional rate of revolution of the output shaft without taking the leaks into account is determined by the following formula:

$$n_p = n''_m \frac{\tan \gamma}{\tan \gamma'},$$

where n''_m - is the rate of revolution of the aircraft engine taking into account the transmission ratio of 14-12-13 of the reducing gear.

In this way, the satellite pinions being rotated over two channels: by the pull, proportionally to the speed of the aircraft engine, and by the crown pinion, proportionally to the speed of the hydraulic motor, increase the rate of revolution of the sun gear and accordingly of the output shaft n = const:

$$n = n'_m + n_p = n'_m + n''_m \frac{\tan \gamma}{\tan \gamma'} = \text{const.}$$

Here, the flow of power from the aircraft engine to the generator proceeds over two paths: directly to the mechanical transmission AE-11-12-13-G and through the regulated hydraulic transmission AE-HP-HM-14-12-13-G.

If the rate of revolution of the aircraft engine increased ($n'_m > n$), then disk 5 deviates automatically towards the motor operating condition of the hydraulic pump. Hydraulic pump HP becomes a motor, and hydraulic motor HM becomes a pump. Because of this the hydraulic pump, together with the crown pinion 14, begins to rotate in the opposite direction, slowing down the rotation of the satellite pinions 12; accordingly the rate of revolution of the output shaft decreases to n = const.

EFFICIENCY AND WEIGHT OF FLUID DRIVES. The power losses in the hydraulic drive result in heating of the hydraulic fluid. To avoid overheating, it is necessary to have a sufficiently large volume of it and cooling devices, which increases weight.

The efficiency of the fluid drive has its higher value η_{max} under the calculated conditions, when the power is transmitted mechanically. In this case one of the hydraulic machines is idling (more precisely it provides compensation for the leaks in order to maintain the pressure in the system), and the other at the same time is stationary and holds back the auxiliary link of the differential mechanism. Therefore, power losses in the hydraulic part of the drive under the calculated operating conditions, are insignificantly small. Under conditions which differ from the calculated conditions, the mechanical capacity is transmitted with an efficiency of η_{max} while the hydraulic power is transmitted with an efficiency of a simple hydraulic drive. Upon the deviation from the calculated operating conditions on either side, the efficiency of the drive drops according to the hyperbolic curves from the η_{max} value to the minimum value.

Most of the time the fluid drive operates under operating conditions close to the calculated, and therefore, its efficiency in this case is close to the maximum (0.85-0.95).

The specific weight of the fluid drive is approximately equal to its 0.6-1 kg/kw for the 1:3 range of speed regulation, the calculated operating conditions being located in the middle of the range.

For a turbine engine with a speed range of 1:1.3 the hydraulic drive will have a smaller weight. The reducing gear in this case should be calculated for a capacity exceeding the rated capacity by only 13%

while the hydraulic machine should possess a capacity equal to 13% of the rated capacity. The specific weight of the fluid drive in this case will be about 0.5 kg/kw.

8. Simple Pneumatic Drive.

In the simple pneumatic drive with a turbine, the entire power of energy is controlled and transmitted in only 1 direction from the aircraft engine to the generator.

The turbine of this drive is supplied with compressed air from the aircraft engine compressor. The energy for rotation is obtained through the expansion of the air in the nozzle equipment of the turbine.

The power developed by the turbine depends on the weight consumption of the air, and the temperature drop in it. The weight consumption of air is determined by the pressure and temperature of the air supplied, the efficiency of the turbine, and the cross-section of the nozzle.

With the increase of the flight altitude the weight consumption of air drops, and the temperature drop in the turbine increases. Consequently, the power developed by the turbine is almost independent on the flight altitude.

With the increase of the flight velocity, the power developed by the turbine increases, therefore, the turbine is planned for operating under low-gas conditions. During cruising speed the power yielded by the turbine is artificially decreased by throttling the air at the turbine's input or by changing the cross-section of the nozzle. The latter yields the greater effect, but it complicates the design and increases the weight of the turbine.

Short-comings. 1. The low efficiency of the air turbine which depends on the degree of automatic expansion (ratio between the pressures at the input and output). Its maximum value does not exceed 0.6.

2. Air from the aircraft engine compressor at high altitude causes a considerable decrease of the thrust or power of the jet engine, although they share in the total air mass in the compressor is not large.

3. The drive is not economical, since the entire flow of compressed air, bled from the aircraft engine, results in an additional consumption of fuel and the corresponding increase of the flight weight of the aircraft.

Drives with a gas-turbine are drives of the direct flow of energy and may operate on exhaust gases from the main aircraft engines, or with fuel-air mixtures.

Turbines with exhaust-gas operation, do not have their own compression chambers, are simple in design and have a small weight and dimension.

Turbines, operating on fuel-air mixtures, have a more complicated design because of installation before the nozzle apparatus of combustion chambers in which the additionally delivered fuel is burned. This decreases the air consumption drawn from the aircraft engine compressor, as compared to the air turbine of the same capacity.

9. Pneumatic Differential Constant Speed Drive with a Pneumatic Turbine.

In fig. 2.14 we show a simplified diagram with characteristics of a pneumatic differential drive with constant speed and a pneumatic turbine.

The drive has the following principal elements:

1. Differential reducing gear, totaling up two flows of energy: non-regulated which arrives from the aircraft engine shaft, and regulated which is drawn forth from the pneumatic turbine.
2. Pneumatic turbine which on the command from the regulation system controls a part of the energy flow, providing in this way the constant speed for revolution of the generator.

In the pneumatic turbine the kinetic energy of the flow of compressed air is used which is drawn from the compressor of the aircraft engine or from another source of air-energy. As the operating device it is recommended to use the radial turbine, which has substantial advantages over the axial turbine.

3. The regulation system, which creates the necessary operating conditions for the turbine. In this system the speed regulator reacts to the deviations of the generator's rate of revolution from the nominal and produces the corresponding signal to the servo-mechanism, which transmits the command to the sleeve mechanism of the nozzle apparatus and regulating valve for the incoming air; the latter correct accordingly the turbine's operating condition. The system provides for a special corrector, reacting to the delineation of the frequency and the non-uniformity of the load on the generators when they are working parallel, and gives the corresponding signal to the servo-mechanism.
4. The system of protective devices, which operate automatically when individual elements of the regulating systems have failed. If the drive's speed exceeds the maximum permissible speed of the generator or turbine, or the minimum speed of the generator, then the drive

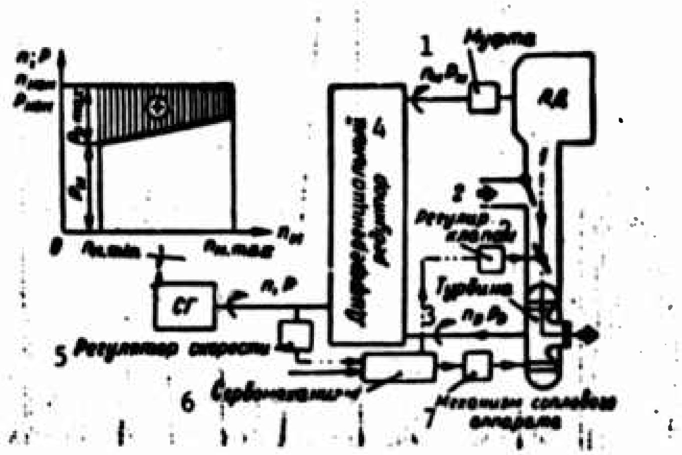

Fig. 2.14. Simplified diagram and characteristics of the pneumatic differential drive with a pneumatic turbine: 1 - air drawn from the compressor; 2 - entry of air during starting, operation on the ground and during power supply from another engine.

Key: 1. Sleeve, 2. regulating valve, 3. turbine, 4. differential reducing gear, 5. speed regulator, 6. servo-mechanism, 7. nozzle apparatus mechanism.

automatically disconnects from the power system.

It is advisable to design the drive as a multi-purpose apparatus, which decreases the weight and the dimensions of the entire set of the equipment.

The drive solves the following problems:

1. It assures the starting of the main aircraft engine by means of a turbine upon delivery of compressed air from the turbine unit aboard the aircraft or on the ground, and also from the operating aircraft engine of an airplane with several engines.
2. When the aircraft engine stops during flight, the turbine, which obtains compressed air from the operating aircraft engine or from the auxiliary source of air energy, provides for a constant speed of the generators' revolution.
3. It assures the working of the electrical system on the ground, including the generator, when the aircraft engine is not working. In this case, in order to rotate the turbine, compressed air is used from the turbine unit, either aboard the aircraft or on the ground.
4. It assures the constant speed of the generator under all flight conditions and operating conditions of the aircraft engines, including the low gas conditions. In this case the principal power from

the aircraft engine is transmitted mechanically, and the regulated part by means of the turbine.

Advantages. 1. Relative design simplicity.

2. Reduction of the number of rocking kinematic pairs, which increases reliability.

3. Absence of need for a cooling system.

4. Possibility of combining a number of functions: drive, aircraft-engine starter, cooler, etc.

5. Low weight of the structure.

Short-comings. 1. Difficulty of reversing the turbine; non-reversibility of the turbine results in excessive power and reduction of efficiency of the turbine.

2. Presence of "soft" regulating characteristics, which are undesirable when the generators are operating in parallel.

3. Low efficiency, especially with a wide range of variations in the air's parameters.

In fig. 2.15 we present the simplified diagram of the pneumatic differential drive with constant speed and a pneumatic turbine of the Air Research Company.

The transmission mechanism of the drive consists of two combined planetary gear transmissions, interconnected by a common angular gear with internal engagement. The input shaft, which passes through the hollow rotor of the generator is connected with the guide of the planetary gear. The sun pinion of the generator is connected one to a pair, and the sun pinion of the turbine with another pair of the planetary transmission.

The drives provides three different operating conditions:

1. Starting of the aircraft engine by the turbine. During starting the angular gear 9 is stopped by the starting engagement sleeve 11. The power from the turbine is transmitted to the aircraft engine by a geared transmission T-2-4-6-8-10-1-AE, which assures a transmission ration required for starting.

2. Production of a constant generator speed from the turbine alone. This response to the regime of a non-operating aircraft engine when the guide of the planetary transmission is motionless, is given. The power is transmitted from the turbine to the generator through a rotating angular gear with internal engagement and a transmission ratio, responding to the constant speed conditions. Kinematically, the transmission is performed in the direction of T-2-4-6-8-9-7-5-3-SG.

3. Producing a constant speed of the generator upon transmission of power from the aircraft engine with regulation of the revolutions by the turbine. During normal work of the drive, most of the power is

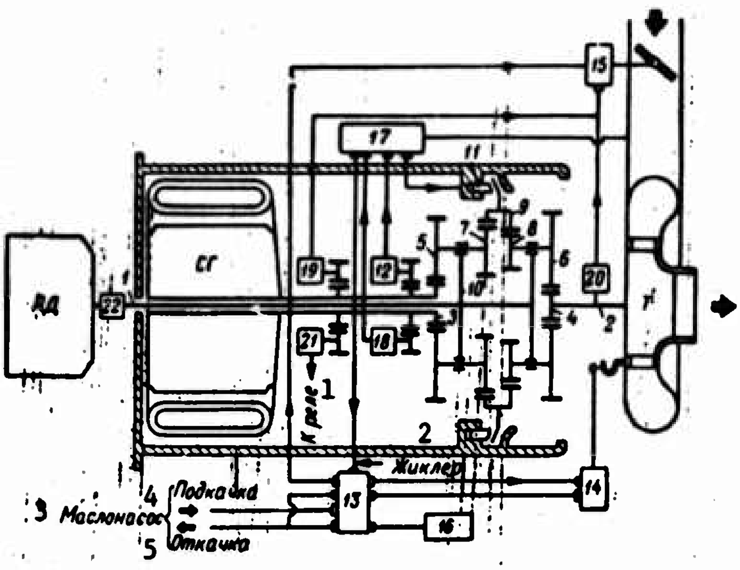

Fig. 2.15. Simplified diagram of a pneumatic differential constant speed drive with a pneumatic turbine:
AE - aircraft engine; G - turbine; SG - synchronous generator; 1, 2 - shafts of the aircraft engine and turbine; 3, 4 - sun pinions of the generator and turbine: 5,6,7,8 - planetary gears of the generator and turbine; 9 - angular gear; 10 - drive; 11 - pneumatic starting engagement sleeve; 12 - pneumatic speed regulators; 13 - pneumatic servo-mechanism; 14 - hydraulic sleeve mechanism; 15 - pneumatic regulating and cut-off valve; 16 - corrective device; 17 - starting selector electrical and pneumatic device; 18 - pneumatic starter switch; 19 - pneumatic switch for maximum rpm of generators; 20 - pneumatic switch for maximum rpm of turbines; 21 - pneumatic switch for minimum rpm of generators; 22 - pneumatic engagement sleeve.
Key: 1. to the relay, 2. jet nozzle, 3. oil pump, 4. pumping in, 5. pumping out.

delivered from the aircraft engine to the generator mechanically, to transmission AE-1-10-5-3-SG, while the speed regulation and the corresponding part of the capacity is provided for by the turbine through transmission G-2-4-6-8-9-7-5-3-SG. The turbine operates with air drawn from the aircraft engine compressor or from the jetstream.

When the speed of the revolution of the aircraft engine changes the speed of revolution of the angular gear 9 changes accordingly through the planetary transmission, connected with the sun pinions of the turbine. Then the rate of revolution of the turbine changes on command of the regulation system, in order to produce constant revolutions in the generator.

THE REGULATION SYSTEM includes the following basic elements:

Pneumatic speed regulator 12, reacting to the rate of revolution of the generator by means of a centrifugal mechanism and sending a pneumatic signal to the servo-mechanism.

Pneumatic servo-mechanism 13, which receives the signal of the speed regulator and sends a hydraulic signal to the sleeve mechanism of the nozzle apparatus and the pneumatic signal to the regulating valve.

Hydraulic sleeve mechanism 14, receiving the command from the servo-mechanism changes the position of the nozzle apparatus of the turbine, regulating the speed of revolution of the turbine, which provides the constancy of the speed of revolution of the generator.

Pneumatic regulating and cut-off valve 15, which on command of the servo-mechanism regulates the delivery of air to the input of the turbine, and under emergency conditions closes completely the air inlet into the turbine.

Correction device 16, which reacts to the deviation of the frequency and non-uniformity of the load on the generators connected to common busbars, which produce the corresponding signal to the servo-mechanism.

Starting selector electrically and pneumatic device 17.

Pneumatic starter switch 18.

With a full range of changes of the external conditions during an established regime, the regulation system maintains the generators' frequencies with a precision of
$\pm$ 1% and without a correcting device, and
$\pm$ 0.1% with a correcting device.

THE SAFETY DEVICE SYSTEM goes into action automatically upon the appearance of defects in the speed regulation system and turns on the following basic elements:

Pneumatic switch for the maximum speed of generator 19, reacting by means of the centrifugal mechanism to excess of the maximum permitted speed of the generator, acts on the cut-off valve, which closes the access of air to the turbine.

Pneumatic switch for the maximum speed of turbine 20, reacting by means of the centrifugal mechanism to the excess of the maximum permissible speed of the turbine, acts on the cut-off valve which stops the access of air to the turbine.

Pneumatic switch 21 for the minimum speed of the generator switches off the load by means of a relay when the speed drops below the permissible limit.

Electrical clutch 22 for engaging the shafts of the drive in the aircraft's engine, which provides for a disconnection of the shafts during emergency conditions.

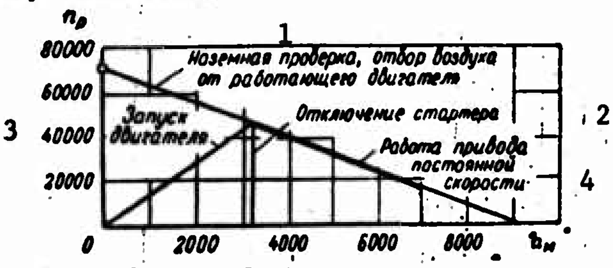

Fig. 2.16. Dependence of the revolutions of the turbine on the revolutions of the engine: n_m - revolutions of the engine, n_p - revolutions of the turbine.

Key: 1. Ground check-up, bleeding of air from the operating engine. 2. Switching of the starter. 3. Starting the engine. 4. Work of the constant speed drive.

The drive turbine under operating conditions works at low rpm and it is quite improbable that it will go out of commission because of an excess of speed of revolution.

The transmission system consists of common gears, which provide sufficient reliability of the design.

In fig. 2.16 we show the curve of the relationship between the speed of revolution of the turbine and the speed of the driving shaft of the aircraft engine.

When air is delivered from an outside source, and the revolutions of the input shaft of the engine are equal to 0, the turbine operates at a constant speed of 70,000 rpm. The drive in this case performs the role of the reducing gear with an output velocity of 8000 rpm.

When the aircraft engine is started the angular gear is retained in the stationary position by the starting clutch. At the moment of disconnection of the starter the speed of the turbine reaches 46,000 rpm.

When the power is delivered from the operating aircraft engine in the speed range of low gas (4,000 rpm)to the maximum (7,000 rpm), the rate of revolutions of the turbine changes respectively from 41,000 to 8200 rpm.

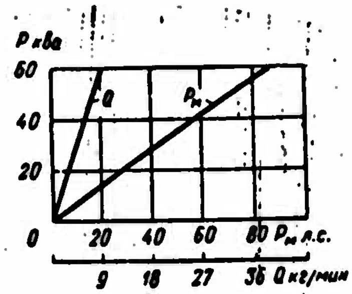

Fig. 2.17. Relationship between the output capacity of the generator and the power drawn from the engine (mechanical and air): P - power yielded by the generator; P_m - mechanical power drawn from the engine; Q - air-consumption drawn from the engine.

In fig. 2.17 we show the relationship curve between the output capacity of the generator and the power drawn from the aircraft engine through the mechanical driving shaft, and the amounts of air drawn from the aircraft engine compressor and passing through the turbine. From the curve it follows, that with an output capacity of the generator amounting to 30 kw, a mechanical power of 42.5 hp and airpower of 5 kg/min are drawn from the aircraft engine.

The mean value of the heat transfer into the oil amounts to 3.4 hp (or 34 kcal/min) for 60 kw of the unit and 2.4 hp (or 24.2 kcal/min) for the 20 kw unit, which approximately corresponds to 1/5 of heat transfer into the oil for the equivalent hydraulic drive.

The design of the drive may be such, that the distribution of capacity between the driving shaft of the aircraft engine and the input shaft of the turbine will correspond to the air temperature at the output from the turbine, amounting to 90°C. This air may be used for cooling the oil, the generator, and other units.

The drive has the following prospects:

1. It is potentially possible to use it in an autonomous system of generator and oil cooling at high-speed aircraft, using the high-speed thrust energy for regulating the speed of revolution of the turbine, enabling us to reduce the air temperature at the output to the required level through expansion.
2. Since the drive may operate with air drawn from the aircraft engine, a special engine, or the high-speed thrust, an ideal device for aircraft with a combined turbojet engine.
3. The drive is ideal for nuclear power installations, since it can turn the engine for a long time, using the energy of the air drawn.

10. Pneumatic Differential Constant Speed Drive with a Pneumatic Regulation Unit.

In fig. 2.18 we show the simplified diagram and characteristics of the pneumatic differential constant speed drive with a pneumatic regulation unit.

The drive has the following basic elements:
1. Differential reducing gear.
2. Rotary pneumatic engine.
3. Regulation system.
4. Protective device system.

The purpose, the operating principles, merits and short-comings of the drive are the same as those of the drive described in paragraph 9. The specific feature of the pneumatic engine's work are obvious from the simplified diagram.

The basic power for rotating the generator is taken from the shaft of the aircraft engine by means of a mechanical reducing gear, while the pneumatic (rotating or volume) unit, controlling a part of the energy consumed, provides a constant rate of revolution for the generator.

Pneumo-static devices primarily use potential air energy, compressed by the aviation motor compressor. The pneumatic motor may be a dual rotor pump, which is easily reversed, leading to a decrease in its power and an increase in efficiency, while its more "rigid" control characteristic improves parallel operation.

In dual rotor pumps, the contact of the rotors with each other and with the body walls occurs along the generatrix of the cylinder, not along the curves of the surfaces. As a result of this, slight inaccuracies in assembly cause wear of the operating surfaces, considerable leakage, changes in productivity and efficiency.

The finish of the working surfaces of the rotor requires high accuracy, complicating the manufacturing process.

Figures 2.19 and 2.20 show an overall view and diagram of a pneumo-mechanical differential constant speed drive manufactured by the Plessy firm.

The drive used a reversing system with a differential and a roots type positive displacement blower. At low rotating speed of the motor, compressed air is fed into this machine and it acts as a motor, spinning the generator. At high engine operating speed, the blower rotates in the opposite direction and acts as a brake (compressor), driven by the engine. In this mode, it decreases the rotating speed of the generator, maintaining it constant.

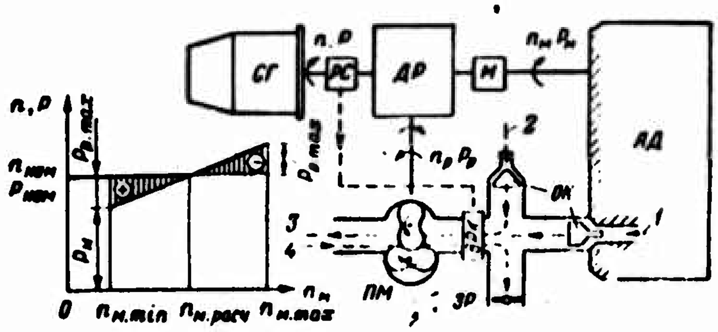

Fig. 2.18. Block diagram and characteristics of pneumomechanical differential drive with pneumostatic control apparatus: PM - pneumomotor; VRK - air regulating valves; DR - differential reducers; OK - back valve; M - sleeve, RS - velocity regulator; ZR - reverse valve; 1 - air collected from compressors; 2 - air intake during start, operating on ground and when supplied from another engine; 3 - air out: upt to cruising mode, when supplied by another aviation motor, during operations on the ground and start; 4 - air intake for cruising and high cruising modes.

When the drive operates between the idle and cruising regimes, compressed air is collected beyond the compressor of the motor 14, passes through air valve 5 and rotates air motor 4. The movement is transmitted to driver 8 through gear box 6 from motor 4. The planetary gear 10, is driven by the motor, as a result of which gear 11 and output shaft 3 connected to it, rotate at the required speed. As the rotating speed of the engine is increased, valve 5 decreases the supply of compressed air to the motor, the rotating speed is decreased and as a result, the output shaft continues to rotate at its previous speed. Air valve 5 in this case controls regulator 1, connected to output shaft 3. This operation continues to a cruising point, that is 75% of the maximum speed of the aviation engine. Under these conditions, the efficiency of the drive exceeds 90%.

Under cruising conditions the number of revolutions of the air-motor decreases to 0. During the subsequent increase of the number of revolution of the engine, the air-motor begins to rotate in the opposite direction, operating as an air-brake (compressor). The direction of the air-movement in this case changes to the reverse. In this case, valve 5 disconnects the main line, leading from the engine, and bipasses the air, going from the roots engine into the atmosphere.

Thus, from the cruising speed to the maximum speed, no air has to be drawn from the aircraft engine compressor, while the entire power for rotating the generator is taken from the aircraft engine mechanically, which assures the highest economy of the system. Thanks to low inertia and small time constant of the engine of this type, a good regulation of the frequency and parallel work of the generators is attained.

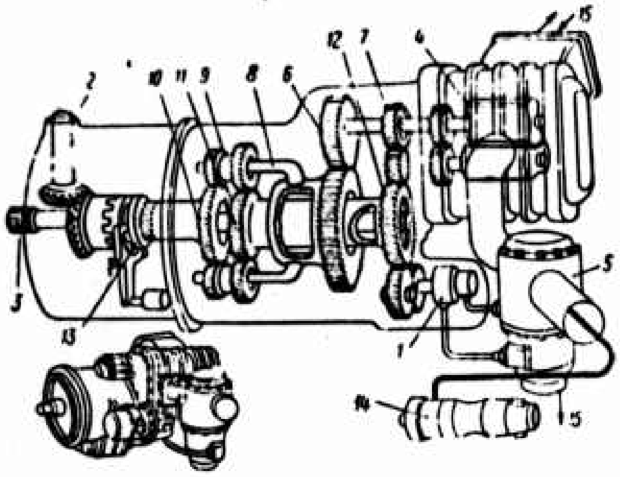

Fig. 2.19. Constant speed drive by Plessy firm: 1 - engine speed regulator; 2 - drive from engine; 3 - output shaft; 4 - air motor; 5 - air valve; 6 - gear; 7 - gear with clutch; 8 - driver; 9 - planetary gear; 10 and 11 - sun gear; 12 - gear with clutch; 13 - motor disconnect clutch; 14 - engine; 15 - direction of movement of air in reverse motor rotation mode.

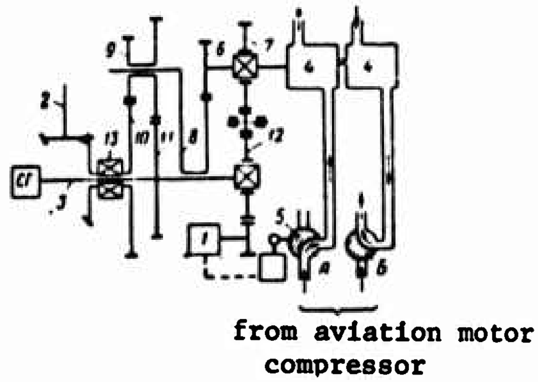

Fig. 2.20. Diagram of constant speed drive with volume air motor: A - motor mode; B - braking mode.

When the aircraft engines are started the compressed air from the ground source or that drawn from the compressor and already started engine turns air-motor 4, clutch 7 is connected automatically, and the engine spins powered by the air-motor by means of gears 7-12-11-9-10. At certain turns, the clutch is disconnected and the units goes into the constant speed drive conditions.

During the work of the drive on a non-operating aircraft engine on the ground, clutch 13 disconnects the drive from the aircraft engine. The compressed air from the ground source is delivered to the air-motor 4. The drive is carried out by a simple reducing gear, consisting of gear 7 and 12, which have a constant transmission ratio between the pneumatic engine and the generator. The air valve 5 maintains a constant calculated speed of the generator.

If one of the aircraft generators has gone out of commission, then rotating the drive from an outside source, we can obtain the energy from the generator installed on it. For this clutch 13 disconnects the drive from the engine, and the air-motor is supplied with air which is drawn from other engines. The operating principle of the drive is the same as on the ground, when the aircraft engine is not working.

Merits. 1. When the aircraft engine turns at a speed of more than 0.75 of maximum (practical flying speeds) the drive does not draw air from the aircraft's compressor and has an efficiency of more than 0.9, providing a high economy.

2. In the drive heat evolution is almost completely absent.

3. The independent oil system of the regulator and the lubricating system increases reliability.

4. The strength of the reducing gear is determined by the starter regime, therefore, it is permissible to install a more powerful generator and have an electrical overload.

5. The drive permits us to adjust the electrical systems on the ground without starting the aircraft engine.

11. Electrical Constant Speed Drives.

Electromechanical drives may be represented by two types: simple and differential. As examples let us examine the electromagnetic sliding coupling, electromagnetic brake, and combined drive.

THE ELECTROMAGNETIC SLIDING COUPLING, presented in fig. 2.21, consists of the driving part 1, connected with the aircraft engine shaft, and the driven part 2, which is on the same shaft with the synchronous generator rotor 3, located inside stator 4.

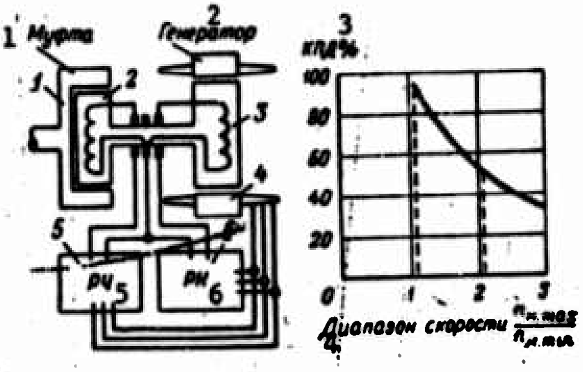

Fig. 2.21. Diagram of the constant speed drive with an electromagnetic sliding coupling.
Key: 1. coupling, 2. generator, 3. efficiency %, 4. speed range, 5. frequency regulator FR, 6. voltage regulator.

The excitation winding of the electromagnetic coupling is located on the driven part 2, and is supplied with direct-current through the frequency regulator.

The excitation winding of the synchronous generator is located on rotor 3 and is supplied with direct-current through voltage regulator 6, which automatically changes the excitation current value, and stabilized the output voltage of the generator.

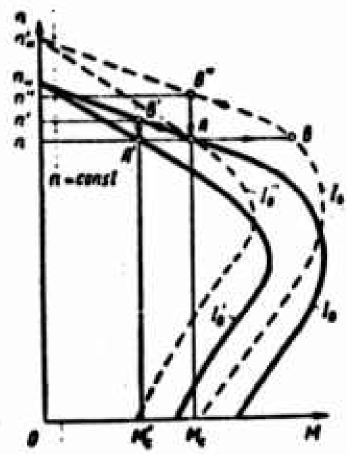

Fig. 2.22. Mechanical characteristics of the electromagnetic sliding coupling.

In the electromagnetic sliding coupling the friction elements are absent, and its mechanical characteristics (fig. 2.22) are analogous to the characteristics of an asynchronous machine. From the characteristics it is clear, that upon a change of the excitation current of the coupling (analogously to the voltage changes at the terminals of an asynchronous machine) the character of the mechanical characteristic $M = f(n)$ changes.

The deviation of the rotation speed of the generator n from the rated speed may occur as the result of a change in the active load of the generator, i.e., the change of the braking-moment M_C or the change in the rate of revolution of the primary motor n_m.

Let us assume that the active load of the generator is decreased, then the moment of resistance decreases proportionally from M_C to M'_C. With the speed n_m of the primary motor unchanged, the speed of the generator increases to n'. In order to maintain the speed of the generator unchanged, the automatic frequency regulator reduces the current of clutch excitation from I_B to I'_B, i.e., by a value with which the mechanical characteristic will pass through point A', located on the line $n = \text{const}$.

Let us assume that the speed of the primary motor increases from n_m to n'_m, then the mechanical characteristics, retaining its shape, will displace upward by $n'_m - n_m$ and the speed of the generator will increase up to n". In order to retain the speed of the generator constant, the frequency regulator decreases the excitation from I_B to I''_B, i.e., so much that the mechanical characteristic would pass through point A.

In this way, upon a change in the speed of the primary motor or the active power of the generator (M_C), the speed of revolution of the synchronous generator rotor is maintained constant by regulating the excitation current of the electromagnetic clutch by means of an automatic frequency regulator.

In an established regime the driving and the driven part of the clutch are acted upon by the same electromagnetic moment M, which does not depend on the rate of revolution, although it differs. The power delivered to the clutch, $P_m = n_m M$, and the power removed from the clutch, is $P = nM$. The difference in the power surmounts to the losses through slipping of the clutch:

$$\Delta P = P_m - P = M(n_m - n).$$

From the formula we can see that with increase of the range of speed variation in the revolutions of the aircraft engine, the losses in the clutch increase and its efficiency decreases. The minimum efficiency of the clutch is determined as

$$n_{min} = \frac{P}{P + P_{max}} = \frac{Mn}{Mn + M(n_{m\ max} - n)} = \frac{n}{n_{m\ max}} .$$

If we do not take into account the minimum slip, equals 3 - 5%, then approximately we can consider that $n \approx n_{m\ min}$, then $n_{min} \approx \frac{n_{m\ min}}{n_{m\ max}}$.

Thus the efficiency of a system with an electromagnetic sliding clutch is inversely proportional to the range of the change in the speed of revolution of an aircraft engine.

The principal short-coming of the magnetic clutch is the fact, that all the slipping energy is evolved in the clutch in the form of heat. From the curve given in fig. 2.21, we can see that with the growth of range of speed variations of the primary motor, the efficiency drops rapidly, and with the 2:1 range, one-half of all the energy must be dissipated in the form of heat. This requires an increase in the weight and capacity of the cooling system. Therefore, electric clutches may be used only in a very small range of speed variations for aircraft engines. For example, in turboprop engines.

ELECTROMAGNETIC BRAKE. In such constant speed drives, we use a differential mechanism and an electromagnetic brake. One of the possible variations of the system is presented in fig. 2.23. The shafts of the differential are connected: 1. with the aircraft engine, 2. with the generator, and 3. with the electromagnetic brake.

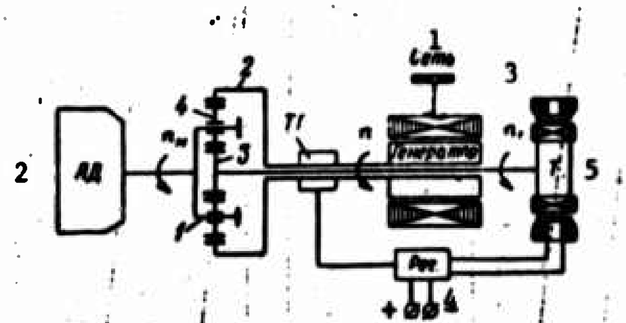

Fig. 2.23. Simplified diagram of a constant speed drive with an electromagnetic brake and a differential. Key: 1. power system, 2. aircraft engine, 3. generator, 4. regulator, 5. brake.

The gear ratio is selected in such a way, that for low gas ground operating conditions (minimum stable number of revolutions of the engines) with an immobile electromagnetic braking device (actually the brake rotates slowly to control the braking moment) the number of revolutions of the a-c generator would correspond to the calculated number. Upon the increase of the number of revolutions of the engine the negative speed of rotation of the brake increases (regulated by the load) and in this way the constancy of the rate of revolution of the a-c generator is maintained. In this case the power from the motor is transmitted to the generator and also to the braking device.

The slippage losses and the efficiency of the electromagnetic brake as well as in the electromagnetic clutch vary in inverse proportion to the range of the speeds of the aircraft engine. Therefore, for the same reasons, the use of an electromagnetic brake is rational only with a small range of variations in the speed of revolution of an aircraft engine.

The electromagnetic brake, in comparison with the magnetic clutch is smaller, especially for a small speed range. Thus, according to the acquired data in work [1], with a range of the speeds of the revolution of 1.1-1.2 the dimensions of the brake are 5 to 15 times smaller than the dimensions of the generator and the corresponding clutch. However, in this case we should take into account additional weight and the structural complexity of the differential.

IN THE COMBINED ELECTROMECHANICAL DRIVE presented in fig. 2.24, as the regulating device, the electromagnetic clutch is used which operates under the residual spinning and braking conditions. The magnetic clutch is switched over from one set of conditions to the other, by a special engagement clutch, which when deprived of current, provides the braking conditions, and provides engagement for the residual spinning conditions. The presence of two regimes reduces losses in the magnetic clutch.

The driving element in the drive is the pole 1, connected with the aircraft engine. The revolutions from the aircraft engine to the generator are transmitted through the gear system 1-4-2-5. Wheel 3 is connected with the armature of the magnetic clutch. The inductor of the electromagnetic clutch may be set by the engagement clutch into the stationary position or be connected to the rotated, by the generator shaft through transmission system 6-7.

<u>The residual spinning conditions</u>. During low gas revolutions, the engagement clutch connects mechanically the inductor of the electromagnetic clutch with the generator's shaft. The inductor receiving its rotating motion and the corresponding excitation, induces electromotive force in the armature. The rotating magnetic field of the ar-

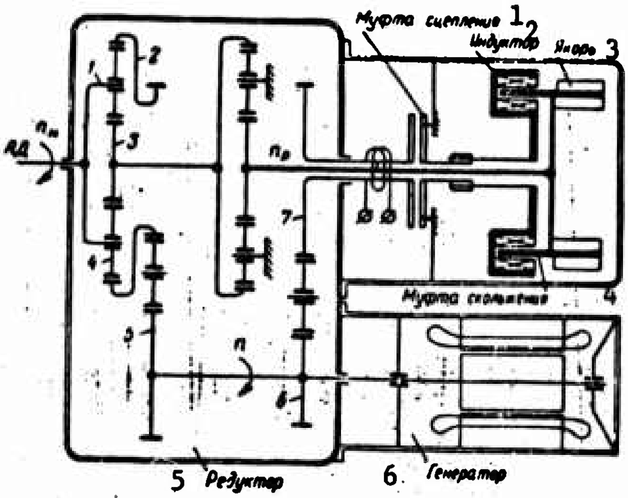

Fig. 2.24. Simplified diagram of a combined electromagnetic constant speed drive.
Key: 1. engagement clutch, 2. inductor, 3. armature, 4. sliding clutch, 5. reducing gear, 6. generator.

mature, interacting with the field of the inductor, imparts a rotating motion to the armature and accordingly to wheel 3, which through satellite pinion 4, increases the rate of rotation of the generator up to the constant rate.

The braking regime. When the aircraft engine revolves at a speed close to the cruising speed, and the rate of revolution of the generator approaches the rated speed, the engagement clutch is deprived of current and fixes the inductor in the stationary state. In this case wheel 3 rotates the armature in the stationary magnetic field of the inductor. The rotating magnetic field of the armature interacts with the inductor's field, which is regulated by the corresponding excitation current, breaks the rotation of wheel 3. With the increase of the speed of revolution of the aircraft engine, the braking effect increases and is transmitted through satellite pinion 4 to wheel 2, connected with the generator. The generator is imparted a constant rate of revolution.

The combined drive possesses short-comings noted above for the magnetic clutch and brake. It is true, that the switch-over device decreases somewhat the process through slipping and decreases the efficiency. However, its application has a practical sense only in a narrow range of speeds of revolution of the aircraft engine.

IN ELECTRICAL CONSTANT SPEED DRIVES the mechanical energy from the aircraft engine is first converted into electric energy.

IN SIMPLE ELECTRICAL DRIVES with a constant speed, shown in fig. 2.25, the entire power, generated by a cascade passes through all the machines.

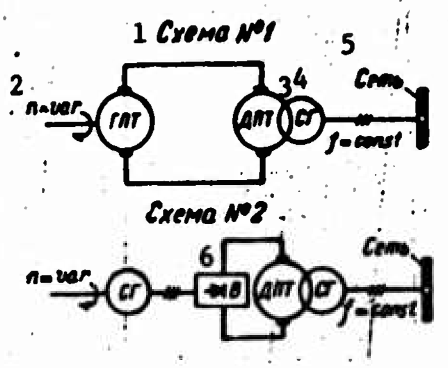

Fig. 2.25. Typical diagrams of a simple electrical constant speed drive:
Key: 1. diagram, 2. a-c generator, 3. d-c motor, 4. synchronous generator, 5. power line, 6. rectifier.

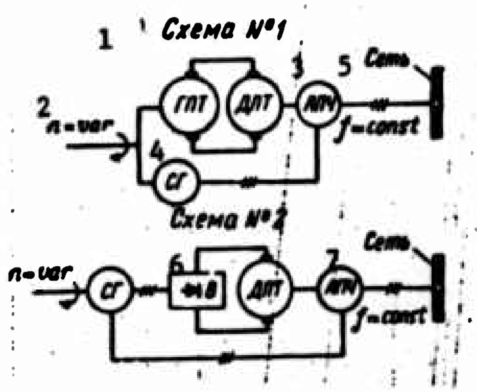

Fig. 2.26. Typical diagrams of a differential electrical drive:
Key: 1. diagram, 2. a-c generator, 3. d-c motor, 4. synchronous generator, 5. power line, 6. rectifier, 7. asynchronous transformer.

The most promising is the system number 2. According to this diagram, the non-conduct a-c generator receives mechanical energy through a reducing gear system from the aircraft engine and together with the rectifier converts it into d-c electric energy, which is used for rotating at a constant speed a single armature transformer, which produces a constant frequency of alternating-current.

IN DIFFERENTIAL ELECTRICAL CONSTANT SPEED DRIVES as shown in fig. 2.26, the power generated by the cascade is delivered over two parallel routes, which converge in a special machine, which carries out the role of a mixer.

The speed (power) mixer in differential systems is an asynchronous frequency transformer (AFC).

The regulation of the cascade's frequency upon a change of the speed of an aircraft engine or the load on the power supply system is carried out by changing the excitation of the d-c motor or the excitation of the generator feeding this motor.

The relative weight of the drives according to the data in work [1] is rather high,,3÷3.5 kg/KvA, its efficiency is relatively low, 0.55 -0.75, and the presence of a collector in one or two of the machines of the cascade reduces the reliability of the electric power supply.

The electrical drive may be used only in a narrow range of speed of the aircraft engine's revolution.

CONCLUSIONS

1. To obtain a constant frequency of a-c generators, mechanical, hydraulic, pneumatic, and electrical constant speed drives are used.

2. Constant speed drives are classified as simple and differential. The efficiency and economy of the differential drive is higher than that of the simple one, these parameters improving with the reversible regulation circuit.

3. Mechanical drives have high conduct pressures between the toroids and the rollers, reaching 30,000 kg (force)/cm^2; they require special lubrication, assuring a high friction coefficient between the rollers and the toroids and good lubrication of the other parts; they are complicated to manufacture.

4. Fluids drives in comparison with pneumatic drives have a complex design and are hard to start at low temperatures, requires absolute air-tightness, purity and cooling of the hydraulic fluid. The most widely used are the differential hydraulic drives with a reversible regulation system.

5. Pneumatic drives with respect to their design are simpler than the corresponding fluid drives, do not require absolute air-tightness, since air leaks do not represents a hazard, do not require heating or cooling. The exhaust air may be used for cooling the generator and other units, which is especially important in supersonic aircraft.

The drives are built in a combined variation form, which provide a constancy of the speed of revolution of the generator under all operating conditions of the motors and permit starting the engines on the ground.

Practical popularity was gained by the differential drives' direct or reversible regulation system.

In the direct system for regulation purposes, the turbine is used, which increases only the rate of revolution.

The turbine is calculated for a minimum energy level of the air drawn from the aircraft engine, and consequently, proves too large for other operating conditions, which results in a reduction of its efficiency into a certain loss of thrust of the aircraft engine. The efficiency of the drive is variable and reaches its maximum value of 0.8-0.85 at rpms which are 0.8-0.85 of the rated rpm.

Table 2.1: Principal Parameters of Certain Constant Speed Drives of Foreign Aircraft.

1 Наименование привода	8 Тип привода	15 Мощность генератора, квт	16 К.п.д	17 Вес: 18 агрегата	17 Вес: 19 полетный	20 Обороты: 21 входа	20 Обороты: 22 выхода	24 Точность частоты: 25 без корректора	24 Точность частоты: 26 с корректором	27 Срок службы	29 Тип самолета
				kg		23 10^3·об/мин		%		28 час	
2 Механический фрикционный	9 Хейсс	30	0,85	40		3—10	8			800	
3 Гидромеханический с гидравлическим дифференциалом	10 Сандстренд	40		38,5		3—10,5	6	±0,5	±0,25	1000	30 Боинг 707, 720 и 727 ДС-8, VC-10
4 Гидромеханический с гидравлическим дифференциалом	11 Джейнерал Электрик	40		22,7		4—8,3	6	±1	±0,25		31 Конвер 880 и 990
		20		15,8		4—8,3	8	±1	±0,25		С-141
5 Гидромеханический	12 Гобсон	22,5		36		4—8,3	8	±1			ДН-121
6 Пневмомеханический с турбиной	13 Эрисерч	60				3,2—9	8	±1	±0,1		Военные самолеты 32
		20				3,2—9	8	±1	±0,1		
7 Пневмомеханический с реверсивным пневмомотором	14 Плесси	30 48 max	<0,9	51		2,62—4,55		±1		2000—4000	БАК-111 33
		60—70 max	<0,9	50		2,6—4,85		±1		2000—4000	Военные самолёты 32

1. Type of drive.
2. Mechanical friction.
3. Fluid with hydraulic differential.
4. Fluid with hydraulic differential.
5. Fluid.
6. Pneumatic with a turbine.
7. Pneumatic with a reversive and pneumatic motor.
8. Type of drive.
9. Hays'
10. Sandstrand.
11. General Electric.
12. Hobson.
13. Air-Research.
14. Plessy.
16. Efficiency.
17. Weight.
18. Of a unit.
19. Flight.
20. Revolutions.
21. Of input.
22. Of output.
23. Rpm.
24. Frequency precision.

25. Without corrector.
26. With corrector.
27. Service life.
28. Housing.
29. Aircraft type.
30. Boeing 707, 720, and 727. DC-8, VC-10.
31. Convair 880 and 990, S-141, DN-121.
32. Military aircraft.
33. MEC-111 (or BAK-111).

In the reversible regulating system, the volume-pneumatic machines of the roots-type and others are used, which yield a higher efficiency as compared with the turbine, and require a lower additional fuel consumption, but are more complicated to build.

6. For the majority of the motors, the drawing of mechanical power is economically more advantageous than drawing of compressed air. However, the comparative characteristics depend substantially on the flight conditions and the load. Therefore, the comparisons are better made with respect to the fuel consumption, taking into account the entire flight schedule. Thus, for example, the additional fuel consumption with a complete drawing of power from the drive, during a typical flight program is: for the fluid drive 0.07-0.1 kg/kwA · hr; for the pneumatic drive with a turbine 0.1-0.2 kg/kwA · hr.

7. In electro-mechanical drives, the transmission ratio is selected from the calculation of the low gas dondition on the ground. With the increase of the speed, the amount of losses increases. When the speed of the aircraft engine increases by two-times, the efficiency reaches 50%, which requires much power for cooling.

8. The drives (depending on the type) react differently to overloads. The fluid drive, calculated for the rated load can sustain 100% overload during 5 sec. through a temporary increase of the fluid pressure, whereas mechanical and pneumatic drives should be calculated taking the overload into account.

In actual practice the mechanical drive operates at 50% of the calculated load, which reduces its efficiency. The pneumatic drive should sustain an overload under more unfavorable parameters of compressed air, and consequently the pneumatic machine will be oversized under all other conditions.

In table 2.1, we give the main parameters of certain constant speed drives of foreign aircraft.

Chapter III. Voltage Regulation in A-C Generators.

1. Specific Features of a Voltage Regulation.

The Voltage regulation system for synchronous generators solves the following problems:

1. It maintains the voltage of the generators at the prescribed level with a required degree of precision during changes of the value and character of the load by acting on the excitation current.
2. It assures stability of the parallel work and uniform distribution of reactive capacities between the generators by acting on their excitation depending on the value and character of the load. The maintainance of the equal power coefficient (cos ϕ) reduces the capacity of the generators for an overload with a reactive current and additional losses of copper.
3. It maintains the stability of parallel work of the generators during short-circuits by forcing excitation.

In developing the simplified circuit diagrams of the voltage regulation system we should take into account a number of specific conditions:

1. Synchronous generators in comparison with d-c generators require two- to three-times greater power for excitation. This is connected with a number of difficulties in regulating voltage by direct action on the excitation circuit and makes it necessary to have an additional machine for the excitation.
2. The degree of voltage asymmetry should not exceed 5%, since the latter causes reverse sequence currents, additional power losses and a considerable reduction of the permissible load on the generator.
3. Under asymmetric loads difficulties arise in the selection of the optimum voltage (linear, phase, mean, or direct sequence), to which the sensitive elements of the regulator should react.

2. Circuit Diagram of the Voltage Regulator's Sensitive Element. Connection of the VR's sensitive elements to the line or phase voltage.

In fig. 3.1 we present a circuit diagram of the sensitive element of a VR directly connected to the line voltage and vector diagrams of voltages during symmetrical and asymmetrical loads.

From the vector diagram it is clear, that under an asymmetrical load the line voltages are distorted, i.e., U_{AC} increased and U_{ab} and U_{BC} have decreased. If the sensitive element of the VR is connected to an increased line voltage (U_{AC}), the regulator will lower the generator's voltage, while if it is connected to the lower voltage, it will raise the voltage generator. Analogous events will occur when phase-voltages are used for this purpose. Thus, when there is an asymmetric phase load, the connection of the VR sensitive element directly to the line or phase voltage of the generator through a rectifier does not assure the required voltage regulation because of the distortion of the triangle of line and phase voltages of the generator.

PUTTING-IN A VR SENSITIVE ELEMENT FOR THE MEAN VOLTAGE.

The putting-in of the VR sensitive element through a three-phase two half-period electrification circuit for the mean voltage of the generator is presented in fig. 3.2.

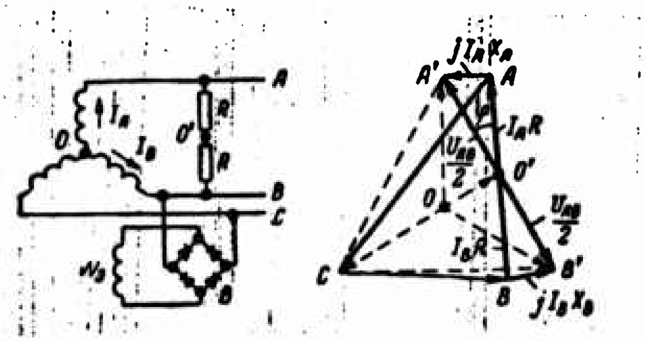

Fig. 3.1. Circuit- and Vector-diagram of the VR sensitive element set for the line voltage.

In the vector diagram of the generator voltages the solid lines correspond to the symmetrical load, and the broken lines to the asymmetrical load.

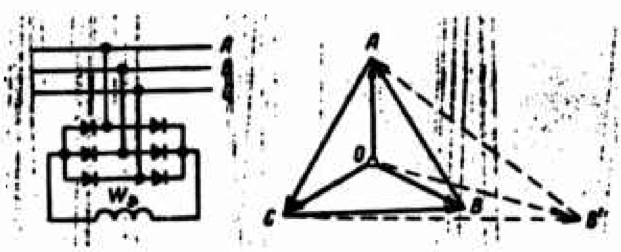

Fig. 3.2. Circuit- and Vector-diagram of the VR senstive element set for the mean voltage.

As we know, the mean value of the rectified voltage of a three-phase two half-period rectifier is proportional to the parameter of the polygon of applied line voltages:

$$U_{rect.mn.} = \frac{\sqrt{2}}{\pi} (U_{AB} + U_{BC} + U_{CA}),$$

where U_{AB}, U_{BC} and U_{CA} - are effective values of the corresponding line voltages; in the line voltages of the generator are the same, i.e. $U_{AB} = U_{BC} = U_{CA} = \sqrt{3}U_f$, then the voltage at the output of the rectifier will be:

$$U_{rect.mn} = \frac{3\sqrt{6}}{\pi} U_f = 2.34\ U_f.$$

Evidently, the degree of asymmetry and the character of the asymmetric load, which determines the shift between the principal voltage vectors of the direct and reverse sequence, will have an influence on the value of the mean rectified voltage. However, as indicated by the investigations in work [10], the asymmetry of line voltages amounting up to 5%, causes an error in the rectified voltage of not more than 0.1%, which is practically permissible for a voltage regulation system. The value of the regulated current does not depend on the frequency, which is supposed to of the factor of the system, therefore it has become popular in actual practice.

CUTTING-IN A VR SENSITIVE ELEMENT THROUGH A DIRECT SEQUENCE VOLTAGE FILTER.

The operating conditions of a synchronous generator are mainly determined by the direct sequence of the vector's of phase and line voltages, therefore, under an asymmetric load, the best circuit diagram of a voltage regulator is the diagram with which the sensitive element reacts to the direct sequence of the voltage.

In order to separate the direct sequence voltages, filters with various circuits are used. For this purpose it is the most expedient to use line voltages, because they always form a closed triangle, and consequently, do not have a zero sequence component.

In the line voltages' system, U_{AB}, U_{BC}, U_{CA}, the direct sequence voltage is determined by the following formula:

$$U = -\frac{U_{BC}\ e^{-j30^\circ} + U_{CA}e^{+j30^\circ}}{\sqrt{3}} = -\frac{e^{-j30^\circ}}{\sqrt{3}} [\dot{U}_{BC} + \dot{U}_{CA}e^{+j60^\circ}].$$

From this formula it is evident that in order to obtain the direct sequence voltage it is necessary to add up the vectors proportional to

$\dot{U}_{BC}$ and U_{CA}, turning them by - 30° and + 30° respectively. This is performed by means of filters, one of the diagrams and the vector diagram which is given in fig. 3.3.

If we select the filter elements X_L, R_1, R_2 and X_C, in such a way that the vector of current $\dot{I}_1$ would lag behind the voltage in vector U_{BC} by 30°, and the vector of current $\dot{I}_2$ would be ahead of the voltage in vector U_{CA} by 30°, then vector $\dot{I}_1 R_1$ in proportion to the line in voltage U_{BC}, will be shifted with respect to vector $\dot{I}_2 R_2$, proportional to the line voltage $\dot{U}_{CA}$, by 60°, and the total vector $\dot{U}_{ED}$, will be proportional to the direct sequence voltage $\dot{U}_{ED} = K\dot{U}_1$.

In this way, the sensitive element of the voltage regulator should be put in to points D and E of the direct sequence voltage filter.

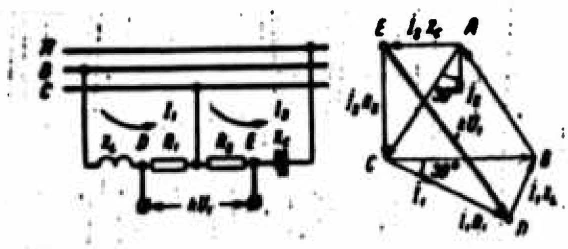

Fig. 3.3. Block and vector diagram of the direct sequence voltage filter.

The direct sequence filters may be used with a strictly constant generator frequency, since in the opposite case the filter will yield great distortions due to changes in the resistances, X_L and X_C.

3. Automatic Voltage Regulators in Synchronous Generators.

The voltage of synchronous generators is regulated automatically by means of carbon and non-contact voltage regulators.

Depending on the system of the generator, the voltage regulator acts directly on the excitation current of the generator or on the excitation current of the exciter.

CARBON VOLTAGE REGULATORS. In synchronous generators which have as an exciter a d-c generator, the automatic voltage regulation may be performed according to the circuit diagram given in fig. 3.4.

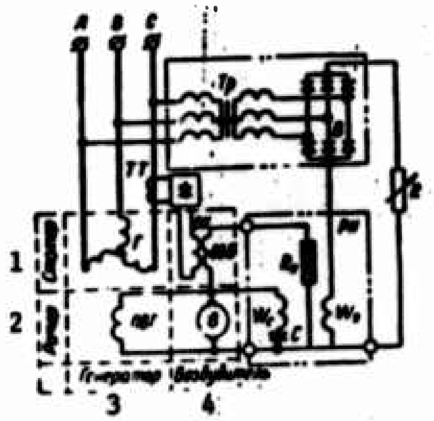

Fig. 3.4. Circuit diagram of a carbon voltage regulator of the synchronous generator, excited with an exciter.
Key: 1. stator, 2. rotor, 3. generator, 4. exciter.

As the sensitive element the operating coil W_e of the carbon regulator is used directly, which is connected to the mean line voltage of the generator through a three-phase transformer and two half-period rectifier.

In order to increase the stability of voltage regulation, a flexible feed-back is used, consisting of capacitor C and additional windings W_c, which form a stabilizing circuit.

With a considerable load-variation, the generator may find itself under the conditions of the non-working sector of the regulator's characteristic, as a result of which the strong decrease or increase of the voltage is possible. To eliminate such phenomena, sometimes an automatic compounding is used by means of a current transformer CT, which sends to the correcting excitation winding of the generator or exciter additional excitation current, proportional to the load current. The compounding current in all the cases counteracts the voltage changes at the terminals of the generator, and in this way simplifies the conditions of the regulator's work stability.

NON-CONTACT VOLTAGE REGULATORS WITH MAGNETIC AMPLIFIERS are the most promising from the point of view of work stability, rating the precision, reliability, and operating convenience. Such regulators became widely used mainly for regulating a voltage of non-contact synchronous generators or their exciters. They can be successfully used instead of carbon voltage regulators in combination with the conventional synchronous generators.

In fig. 3.5 we present a simplified circuit diagram of a non-contact voltage regulator with a two-cascade magnetic amplifier MA1 and MA2.

The sensitive element here is the voltage meter VM connected to the line voltage of the generator. It consists of a saturated choke-

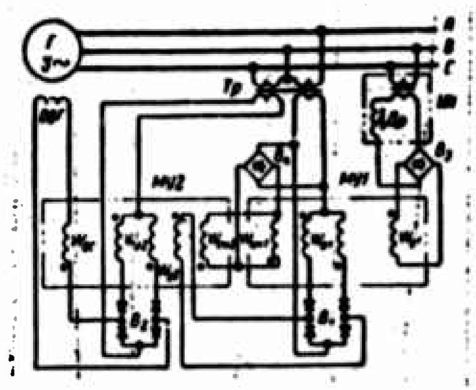

Fig. 3.5. Simplified circuit diagram of a non-contact voltage regulator with a two-cascade magnetic amplifier.

well CC with a non-linear characteristic, the input-current of which goes to the control winding W_{y1} of the magnetic amplifier MA1.

The selection of the working point on a characteristic of the magnetic amplifier MA1, is performed by means of a displacement circuit W_{cm1}, which in essence plays the role of a line channel of the voltage meter. The displacement coil W_{cm2} serves for selecting the working point on the characteristic of MA2 and self-excitation of the generator.

The magnetic amplifiers are made with an internal feed-back, while the output amplifier, connected to the winding of the generator's excitation, is equipped also with an additional feed-back, which makes it possible to increase substantially the coefficient of amplification, with simultaneous decrease of a number of coils of the regulating winding [redacted] to improve the dynamic properties of regulation.

The operating conditions of magnetic amplifiers are selected in such a way that upon the increase of the regulating signal of the first amplifier, its output current would increase, and upon the increase of the regulating signal of the second amplifier, to the contrary, it would decrease. This makes it possible to compensate mutually the displacement of the amplifiers' characteristics, which take place during fluctuations of temperature and frequency of the feeding voltage.

With the rate of the generator voltage through windings W_{cm1} and W_{y1}, identical currents flow, which create opposite magnetizing fields of the same value. Upon the deviation of the generator voltage upon the rated value, the output current in the circuit of the saturated choke-coil CC, into which the regulating winding W_{y1} is included, changes by a large value in comparison with the current in the displacement winding W_{cm1}. The value of the current in the regulation winding W_{y1} determines the value and direction of the resulting magnetic flow, and the output signal of MA1.

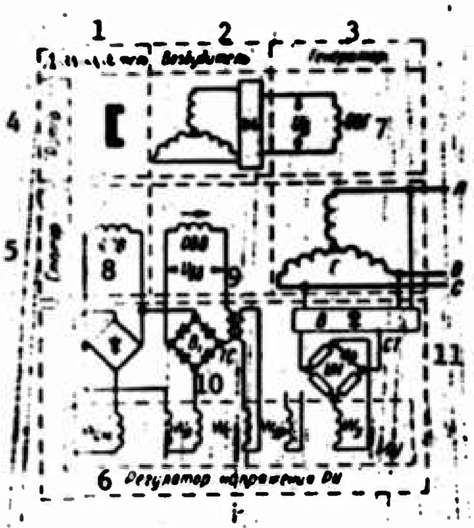

Fig. 3.6. Simplified circuit diagram of the non-contact voltage regulator with a cascade magnetic amplifier.
Key: 1. booster exciter, 2. exciter, 3. generator, 4. rotor, 5. stator, 6. voltage regulator VR, 7. generator excitation winding GEW, 8. armature booster exciter ABE, 9. exciter excitation winding EEW, 10. stabilizing transformer TS, 11. stabilitron ST.

The output signal from the magnetic amplifier MA1, goes to the control winding W_{y2}. The magnetic amplifier MA2 changes accordingly the current in the generator excitation winding GEW, restoring the voltage of the generator to the rated value.

The regulator, according to this circuited diagram, possesses a sufficiently rapid action and control precision of the order of $\pm$ 2%.

In fig. 3.6 we present the typical circuit diagram of a noncontact voltage regulator with a one-cascade magnetic amplifier. The diagram of the regulator is given for the non-contact synchronous generator.

The sensitive element of the regulator is the voltage meter VR, connected through rectifier R for the mean voltage of the generator. The VR consists of a measuring bridge, into one arm of which the stabilitron ST is connected. The bridge is balanced in such a way, that under the rate of the generator voltage the voltage at its output is equal to zero. The VR output is connected to the control winding W_y of the magnetic amplifier MA. The direction of the current in the control winding is determined by the sign of mismatch with respect to voltage.

The displacement winding W_{cm} provides a booster magnetization for the magnetic amplifier MA, providing self-excitation for the generator and work of the magnetic amplifier at the prescribed sector of its characteristic.

The displacement winding W_{cm} and the working winding W_p of the magnetic amplifier are supplied from the armature winding of the booster exciter ABE.

To the output of the magnetic amplifier through the rectifying bridge B_1 the excitation winding of the exciter AEW is connected, in series with which the primary winding of the stabilizing transformer TS is connected, intended for raising the stability of the system's work during the transition stages. The secondary winding of TS is connected to the stabilization winding W_{ct}. With parallel work of the generators, the reactive capacities are distributed uniformly by means of an equalizing winding W_{yp}.

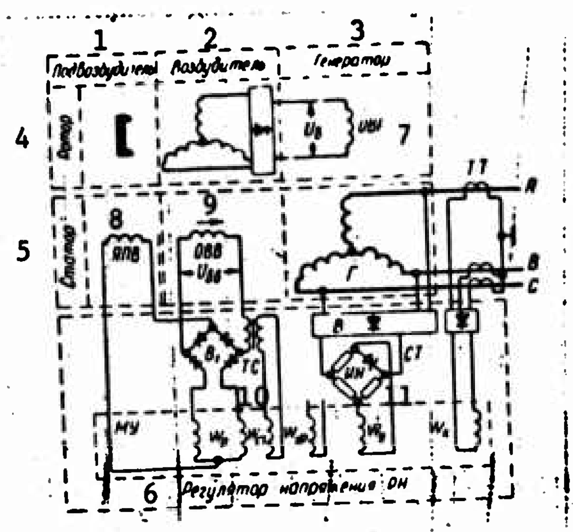

Fig. 3.7. Simplified circuit diagram of a non-contact voltage regulator with a magnetic amplifier with internal positive feed-back and compounding.
Key: 1. booster exciter, 2. exciter, 3. generator, 4. rotor, 5. stator, 6. voltage regulator VR, 7. generator excitation winding GEW, 8. armature booster exciter ABE, 9. exciter excitation winding EEW, 10. stabilizing transformer TS, 11. stabilitron ST.

In this way, the work of the regulator appears in the following form; the deviation of the generator voltage from the rated value is detected by the AR, which changes the current in the control winding W_y of the magnetic amplifier accordingly, the latter changes the current in the exciter's excitation winding EEW. The exciter changes the current in the generator's excitation winding GEW, restores the generator voltage to the rated value.

In fig. 3.7 we show the simplified circuit diagram of a non-contact voltage regulator, in which the magnetic amplifier is used with self-booster magnetization (with internal positive feed-back) through winding W_p and with compounding according to the generator load current through winding W_k. The internal feed-back simultaneously performs both the initial booster magnetization, and therefore in the system the W_{cm} winding is absent. The work of the regulator's circuit is analogous to that examined above.

In fig. 3.8 we give the simplified circuit diagram of the non-contact voltage regulator, consisting of a voltage meter VR, magnetic amplifiers MA1 and MA2, and reactive capacity meter RCM.

The voltage meter consists of a bridge circuit, into the three arms of which ohmic resistances R are included and into the force a non-linear element, a stabilitron ST. The bridge itself is balanced in such a way that with the rated generator voltage the voltage at its output is equal to zero. The input diagonal of the measuring bridge is connected to the mean generator voltage through a step-down transformer TR_1 and rectifier. At the output of the bridge, the control winding W_y of magnetic amplifier MA1 is connected.

The single-phase magnetic amplifier MA1 is made with an internal feed-back. Its operating coils W_p receive their feed from the booster exciter circuit through transformer TR. The stabilizing winding W_{ct} is supplied from the stabilizing transformer TS over the primary winding of which falls the excitation current of the exciter. The stabilizing transformer operates only during transient conditions, and sends to the W_{st} winding a signal, proportional to the change in the excitation current, weakening the action of the control winding W_y and raising in this way the stability of the control system.

Over the equalizing winding W_{yp}, flows a current which is proportional to the difference between the reactive currents of generators operating in parallel. The voltage for this winding is taken from the output resistance of the reactive capacity meter (RCM).

The three-phase magnetic amplifier MA2 is made with an internal feed-back. Its operating coils W_p receive their power supply from the circuit of the booster exciter, while the control winding W_y receives it from the output voltage of the magnetic amplifier MA1.

The displacement winding W_{cm} is connected to the linear voltage of the booster exciter through a three-phase rectifier and serves for coordinating the characteristics of amplifiers and self-excitation of the booster exciter.

The load on the magnetic amplifier MA2 is the excitation winding of the exciter EEW.

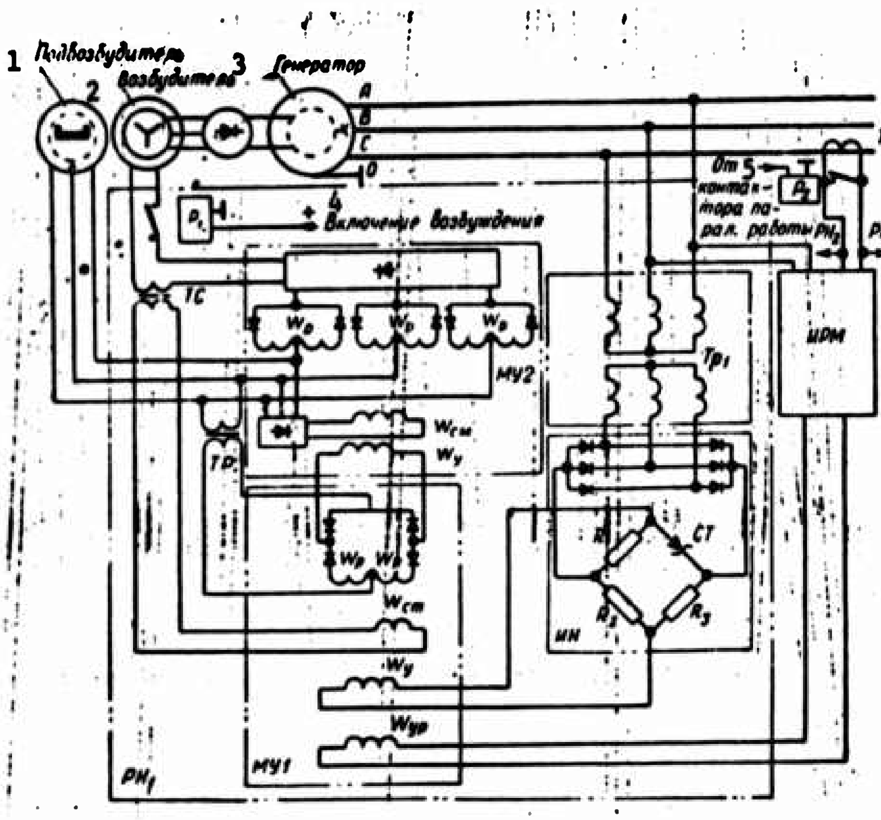

Fig. 3.8. Simplified circuit diagram of a non-contact voltage regulator with a two-cascade magnetic amplifier and reactive capacity corrector.
Key: 1. booster exciter, 2. exciter, 3. generator, 4. switching-on of the excitation, 5. from the parallel work contactor.

The use of the two-cascade amplifier makes it possible to increase the speed of action of the voltage control circuit, that is, to reduce the time constant, which is proportional to the coefficient of the power amplification.

Upon the increase of the generator voltage above the rated (dropping a load) is the output current from the measuring bridge, which increases; the amplifiers decrease the excitation current of the exciter, which decreases proportionally the generator's voltage.

Upon the decrease of the voltage (turning on the load) the reverse phenomenon takes place.

Chapter IV. Parallel Work of A-C Generators.

1. General Information on the Parallel Work of Synchronous Generators.

The parallel work of generators in comparison with separate work, has a number of advantages:

1. The reliability of electric power supply to consumers is improved, since when several generators go out of commission the normal power supply is not disrupted.

2. The installed capacity of the reserve, required for supplying power to consumers when certain generators go out of commission, is decreased.

3. The starting and normal work of the consumers, which exceed with respect to capacity any single generator, is assured.

4. The quality of the electrical energy is improved, because the voltage and frequency stability is raised in the power supply system, especially when high capacity electric motors are started.

SPECIFIC FEATURES OF OPERATING CONDITIONS. The parallel work of aircraft generators in distinction from the ground generators have certain specific features.

1. The power of the generator amounts to 0.5-2% of the power of the aircraft engine.

2. The large range of variations of aircraft engine speeds (1:3 and more).

3. The difference of the values of the speeds in aircraft engines operating in parallel under the same flight conditions.

4. Great accelerations upon changes in the speed of the aircraft engine.

5. Independence of engine control from the operating conditions of the generators.

CONDITIONS FOR CONNECTIONS FOR PARALLEL WORK. When synchronous generators are connected for parallel work it is necessary that the electromotive force and frequency be equal, that the phases of the electromotive force and the sequence of the phases of the generator and the power supply system being connected would coincide.

The reduction of synchronous generators to the state which satisfies the above mentioned requirements is called the synchronization of the generators.

The stability of the parallel work of synchronous generators is assured upon the fulfillment of the following conditions:

1. For synchronizing it is necessary to have an equal and a uniform speed of revolution of the generators and a sufficiently high synchronizing power.

2. In generators with constant speed drives or with commensurable power engines measures should be taken which would include the possibility of the beginning of rocking of the generators.

3. Sinusoidal EMF curves should also be the same, assuring the absence of equalizing currents of higher harmonics, which decrease the stability of the work of the machines and cause additional losses in them.

Two different operating conditions are distinguished:

1. Parallel work of a generator with the power supply system of an infinitely greater power, when the change of the operating conditions of a single generator (change in the excitation or load) has no effect on the voltage and frequency of the power supply system.

2. Parallel work of a generator with a power supply system of a comparable power, when the change in the operating conditions of the generator has a certain effect on the voltage and frequency of the power supply system.

LOAD DISTRIBUTION. During parallel work of the generators the active and reactive loads should be distributed proportionally to their rated capacities, i.e., the generators of equal capacity should operate under a similar load with identical power coefficient, equal to the load capacity coefficient. In this case the power system develops a power which is equal to the sum of the powers of the generators, included in this system, with minimum losses.

With a non-uniform distribution of the active or reactive load the rated capacity of the system is not utilized, since the permissible maximum power of a system is reached under a rated load on one of the generators and the under loading of the other generators.

The active load is transmitted to some generator by acting on its drive, and the generator's excitation change results only in the change in the value and change in the current's value.

CONTROL AND DISTRIBUTION DEVICES. In fig. 4.1 we present a simplified diagram of the parallel work of synchronous generators which are operated by constant speed drives. Each generator has a frequency regulator FR and voltage regulator VR.

When the generators work independently regulators FR and VR maintain the frequency and the voltage respectively at the prescribed level. The stability of the system's work in this case is assured by the proper statism of the regulators, that is, by the dropping speed characteristic in relation to the active load and the dropping voltage characteristic in relation to the full load.

In the parallel work of the generators to the frequency regulator an active power meter is added, APM, and to the voltage regulator a reactive power meter RPM is added. These devices, reacting accordingly to the speed of revolution and their voltage tend to eliminate the imbalance of the load between the generators working in parallel and in this way to assure the minimum drop in the voltage and frequency (speed of revolution) with the growth of the load. At the same time synchronizing devices SD appear, which provide for the connection of the generators for parallel work and retain these conditions under the prescribed parameters of the electric power system.

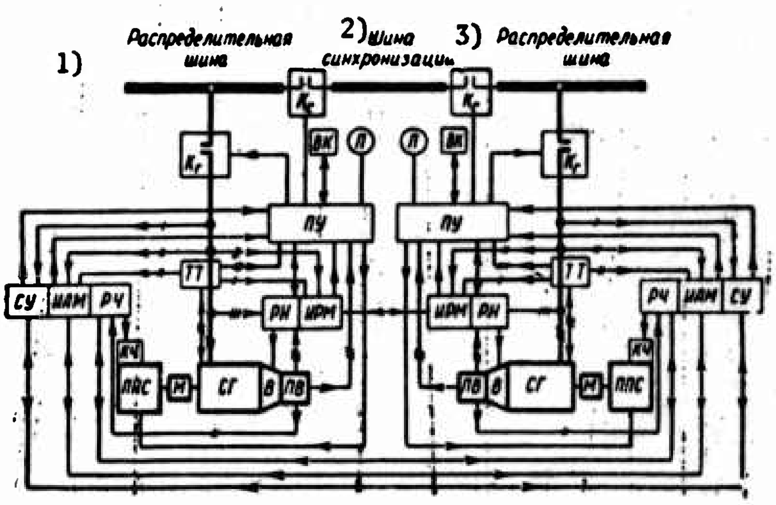

Fig. 4.1. Simplified circuit diagram of the parallel work of synchronous generators:
SG - generator; BE - booster exciter; E - exciter; CSD - constant speed drive; C - free wheeling clutch; VR - voltage regulator; FR - frequency regulator; APM - active power meter; SD - synchronizing device; T - transformer; CP - control panel; S - switch; I - instruments; K_p and K_c - generator in power system's contactors; FC - frequency corrector.
Key: 1. Distribution Bus; 2. Synch Bus; 3. Distribution Bus.

2. Power of the Synchronous Generator.

When a machine's rotor excited with clocks Φ_0, in the stator winding during idling then EMF E_0 is induced.

Under a mixed load under an inductive character, the phase currents of the stator winding lag behind the EMF E_0 by a certain angle ψ (fig. 4.2.). The currents form a rotating field, which in its turn causes varying magnetic linkages during the winding of the stator (armature) Φ_a and the EMF of the reaction of E_a armature.

The sum of vectors Φ_0 and Φ_a, is equal to the magnetic linkage Φ of the resulting field, which is obtained as a result of the supposition of the fields of rotor and stator. The change in the magnetic linkage Φ in the stator winding a resulting EMF E is induced, which may be considered as the sum of E_0 and E_a. The voltage $\dot{U}$ at the terminals of the machine differs from the resultant EMF E by a value of the voltage drop in the dispersion resistance and active resistance of the stator's winding. Due to the small value of these resistances in the qualitative analysis of the machine's work, they can be disregarded and we can consider that the EMF E is equal to voltage $\dot{U}$ on the machine's terminals.

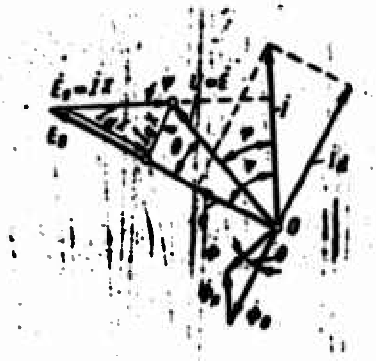

Fig. 4.2. Simplified vector diagram of a synchronous generator.

Thus, EMF E_0 is created by the principal flux Φ_0, whereas voltage U is created by the resulting flux Φ. Each EMF lags behind the flux creating it by 90°, therefore, the mutual position of the fluxes determines also the mutual position of the EMF.

The axis of the principal rotor flux Φ_0 is always ahead of the axis of the resulting flux Φ of the stator by an angle θ and accordingly the vector of EMF E_0 is ahead of the vector of voltage $\dot{U}$. In this case the magnetic flux aligns in the gap are inclined, creating a certain magnetic pull-force. If the generator is idling, then the axis pull of the rotor and stator coincide, i. e., angle $\theta = 0$ and the magnetic lines in the gap are normal to the surface of the poles.

The constant speed drive (CSD), rotating the synchronous generator supplies it with power P. A part of this power is used for compensating the losses: mechanical and for excitation, if the exciter is placed on the same shaft with the generator. The remaining part of the power P_e called electromagnetic, is transmitted from the rotor to the stator electromagnetically, as the result of interaction between the mean flux and the currents in the stator.

At each phase of the stator winding, the E_0 EMF is induced, and the current I flows, which is shifted with respect to the phase by angle ψ. Consequently, the electromagnetic power is developed by the generator, will be determined by the following equation:

$$P_e = mE_0I \cos \psi,$$

where m - is the number of phases of the machine.

From the vector diagram we find that

$$\cos \psi = \frac{U \sin \theta}{IX} .$$

Then

$$P_e = m\,\frac{E_0 U}{X}\,\sin\,\theta,$$

where θ - is the phase shift between the vector of the idling EMF $\dot{E}_0$ and the voltage vector U, lagging behind in time;

X - is the synchronous resistance of the machine, consisting of inductive resistance of the action of armature X_a, and resistance X_l of the diffusion.

When the excitation current is unchanged the idling EMF E_0 = const. If we have approximately assumed that X = const then U = const, the electromagnetic power will depend only on angle θ, i. e., it will change proportionally to sin θ.

The active power $P_a = mUI\cos\phi$, delivered by the generator to the powerline, is smaller than the electromagnetic power by the value of the power loss mI^2r, in the stator's winding. Approximately we can consider that $P_e \approx P_a$.

ELECTROMAGNETIC MOMENT. When the generator is under a load, its rotor is acted upon by the retarding electromagnetic moment M_e, the value of which is determined by the electromagnetic power of the generator P_e, and the mechanical angular rotation speed of the rotor ω:

$$M_e = \frac{P_e}{\omega}.$$

THE ANGULAR CHARACTERISTIC OF THE SYNCHRONOUS MACHINE consists of a periodical curve with positive and negative sectors. The sectors with positive P_e ($0<\theta<\pi$; $2\pi<\theta<3\pi$, etc.) correspond to the generator operating conditions (in fig. 4.3 we show the first sector), and sectors with the negative P_e ($-\pi<\theta<0$; $\pi<\theta<2\pi$, etc.) correspond to the motor operating conditions. When the rotor rotates with a non-synchronous speed θ changes continuously and the machine passes alternatively from the generator to the motor operating conditions and back.

The power developed by the constant speed drive in the prescribed operating conditions, does not depend on angle θ and is portrait by a straight line P_n. After subtraction of the mechanical loss and the losses in the steel, the power will be portrait by a straight line P'_n.

With an established operating regime, ignoring the losses in the stator circuit, the electrical power of the generator P_e, delivered into the power line, will be equal to P'_n.

The intersection of the straight line P'_n and curve P_e, determines two possible regimes of the generator, corresponding to points 1 and 2.

If upon the change of the generator's operating conditions, the rotor will receive an inclination of angle $\Delta\theta$, then for the regime in point 1 the power of the generator will accordingly increase by ΔP. The generator will yield into the power system the greater amount of power than it receives from the CSD, therefore, the rotor will be retarded and the generator will return to the initial operating conditions at point 1. Conversely in point 2, to the positive inclination $\Delta\theta$, corresponds a negative power $-\Delta P$, angle θ will increase even more, and the generator will fall out of synchronism.

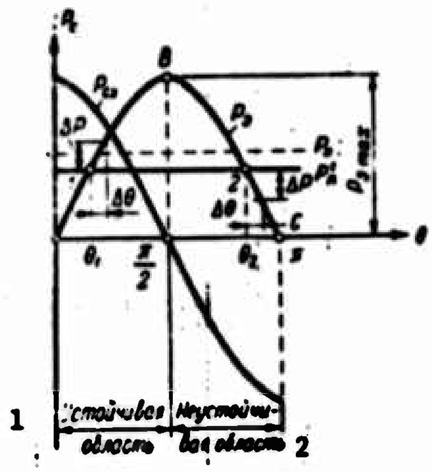

Fig. 4.3. Angular characteristic of the electromagnetic power and coefficient of the synchronizing power of a synchronous generator.
Key: 1. stable region, 2. unstable region.

If we gradually increase the CSD moment then the mechanical power P_n delivered to the generator increases accordingly. The rotor, with respect to the stator begins to shift forward into the direction of the rotation, decreasing angle θ, while the magnetic line in the gap stretches out more, producing an ever increasing counteraction to the CSD moment. The increase of angle θ and of the counteracting generator moment, will continue until the latter will become equal in value to the CSD moment. After this, the further increase of angle θ will cease and the generator will continue to operate with the former synchronous speed, but with a new (greater) angle θ, and its electromagnetic power, will increase proportionally to $\sin\theta$, reaching the maximum value at $\theta = 90°$.

If after this we continue to increase the CSD moment and accordingly the angle θ, the generator will not only develop a greater capacity, but on the contrary will decrease the developed power P_e and moment M_e.

The excess of the rotating moment CSD, with respect to M_e will be used to accelerate the rotor, as a result of which will be a further increase of angle θ and decrease of moment M_e.

In this region, the elastic magnetic lines, which earlier (when θ<90°) had linked the rotor and the stator, are broken off, as a result of which the rotor begins to rotate asynchronously with the flux of the stator. The generator falls out of synchronism, i.e., it ceases to operate in parallel with the power lines.

From the angular characteristics of the synchronous machine, it follows that sector OB, corresponding to the variations of angle θ from 0 to 90°, consists of a region of stable work of the generator, while sector BC corresponding to the variations of angle θ from 90 to 180°, corresponds to the region of unstable work of the generator.

With the increase of θ from 0 to 90° the speed of the growth of electromagnetic power decreases and within the limits between 75-90° it is barely noticeable.

SYNCHRONIZING POWER. Electromagnetic power P_e per unit of angle θ is called the coefficient of the synchronizing power:

$$P_{sch} = \frac{dP_e}{d\theta} = m\frac{E_0U}{X} \cos\theta.$$

Value $\Delta P = P_{sch} \cdot \Delta\theta$ is called the synchronizing power.

The deviation of angle θ by the value of Δθ from the established operating condition, causes an imbalance between power ΔP, resulting in the return of the machine to the initial conditions. The value ΔP is proportional to the steepness of the rise of curve P_e. The greater the P_{sch} the larger are the forces attempting to return the generator's rotor into the initial established operating conditions.

If angle θ = 0 the electromagnetic power developed by the generator $P_e = 0$, and the coefficient of the synchronizing power reaches a maximum

$$P_{sch} = m\frac{F_0U}{X}.$$

With θ = 90° the generator develops the maximum magnetic power $P_{e\,max} = m\dfrac{E_0U}{X}$, and the synchronizing power coefficient $P_{sch} = 0$, and consequently the synchronizing power ΔP = 0, i. e., the generator cannot operate in parallel with other generators.

Practically, even long before $\theta = 90°$ the generator begins to operate not quite stable, and therefore in the synchronous generator angle θ does not exceed 25°, when $\sin\theta = 0.42$, and $\cos\theta = 0.9$, i.e., under the rated conditions

$$P_e < 0.42\, P_{e\,max},\ P_{sch} > 0.9\, P_{e\,max}.$$

OVERLOAD CAPACITY. The ratio between the greatest electromagnetic power, developed by the generator under the rated voltage excitation, to the electromagnetic power developed under the rated operating conditions, is called the overload capacity of a generator;

$$K_o = \frac{P_{e\,max}}{P_{e\,rated}} = \frac{1}{\sin\theta} \approx \frac{P_{max}}{P_{rated}}\ .$$

The overload capacity of a generator is inversely proportional to angle θ.

If the rated capacity of a generator P_{rated} and the voltage of the power system U are prescribed, then it is possible to decrease θ in two ways: by increasing the EMF E_0 through the increase of the excitation current or by the decrease of X. Both methods result in an increase of the volume of the excitation winding, and consequently the increase of the dimensions and weight of the machine.

The overload capacity characterizes the static stability of a generator, i.e., the maximum power, which it can develop during a slow rise of the load, with U = const. The static capacity of a generator operating under a prescribed load increases upon the increase of its maximum electromagnetic moment, that is, upon the increase of E_0 through the increase of the excitation current.

The dynamic stability of the generator, during short-circuits or a sharp change in the load, when the demagnetizing action of the armature's reaction is possible, increases by forced excitation or by compounding.

3. Idle Running of a Generator.

When all the synchronization conditions are fulfilled, the generator, after parallel work, will be under the idle running condition ($\theta = 0$). Depending on the value of the excitation, three characteristic operating conditions for the generators are possible:

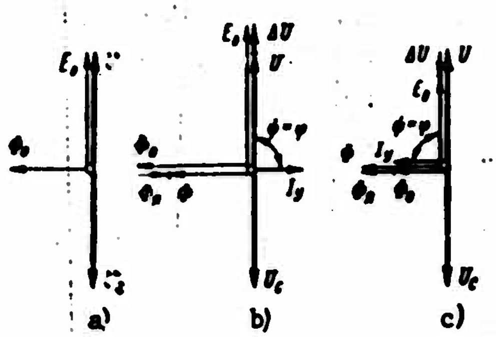

Fig. 4.4. Vector diagram of a synchronous generator running idle. a - normal excitation; b - over excitation; c - under excitation.

1. With normal excitation (fig. 4.4, a) the magnetic flux Φ_0 created by the rotors' pull during its rotation, induces in the winding of the armature and the EMF E_0, equal and opposite in direction to the voltage of the system U_c. Because of this, the current, delivered by the generator into the system is equal to zero, and the EMF E_0 at the same time is its voltage. Therefore, its vector coincides with the voltage vector U with respect to size and phase ($\theta=0$) and consequently, the generator does not give to the powerline either active nor reactive power.

2. Upon overexcitation the magnetic flux of the poles and the EMF E_0 induced in the generator's armature increases. At the same time in the generator's armature a current and a magnetic flux of the armature's reaction appear. In this way, the operating magnetic flux Φ in the machine's airspace will be determined by the difference of the fluxes of poles Φ_0 and the action of the armature Φ_a (see fig. 4.4, b).

Now the EMF E_0 consists of two components: U, which balances the voltage of the power system U_c and ΔU, which balances the EMF induced into the armature by the flux Φ_a and represents a complete voltage drop in the armature:

$$E_0 = U + \Delta U; \quad \Delta U = E_0 - U.$$

The potential difference ΔU causes the appearance of an equalizing current I_y in the circuit of the generator in the power system, which lags by 90° behind ΔU and U, and since $X \gg r$:

$$I_y = \frac{\Delta U}{Z} \approx \frac{\Delta U}{X},$$

where Z, X, and r - respectively, are the full, inductive, inactive resitances of the armature.

This current is purely inductive with respect to the generator and purely capacitative with respect to the voltage of the power system. By creating the longitudinal reaction on the armature, it strives to demagnetize this generator, decrease its EMF, and magnetize the generators operating in parallel with it (increase their EMF).

In this way, upon the overexcitation, and when $\theta = 0$, the generator yields into the power system only the reactive power of the inductive nature.

3. During underexcitation of the generator the working magnetic flux will be determined by the sum of the pole fluxes and the reaction of the armature (see fig. 4.4, c).

In the generator's circuit and in the power system, and equalizing current forms again, the value of which is found similarly to the overexcitation regime. This current lags by 90° from ΔU, and is ahead of U by 90°.

In this way, with underexcitation and when $\theta = 0$, the generator consumes from the power system a reactive capacity of the inductive nature.

4. Work of the Generator in parallel with the Power System During Constant Excitation and Variable Active Power. (i_B = const; P = var).

Let us examine the parallel work of a generator with a power system of infinite power where the voltage and the frequency are constant (U_C = const, f = const) and do not depend on the excitation change or the generator load.

In order to put a load on the generator, connected in parallel with the power system, it is necessary to act on its constant speed drive (CSD) which in its turn changes the rotation moment into electromagnetic (active) power of the generator. In this case the EMF is ahead of the voltage and the generator absorbs the active power, proportional to the sign of angle θ.

During constant excitation of the generator its EMF is constant and consequently the active capacity depends only on the change in the sign of angle θ.

The vector diagram in fig. 4.5, shows a case of transition of the generator from idling operating conditions, when its EMF E_0 is equalized by the voltage of the power system U_c, and a sudden load I, with which vector E_0 is ahead of voltage U by angle θ.

As a result of this lead, there is a certain difference in potential ΔU, which causes in the generator-power system circuit the appearance of current I, which lags with respect to phase from the voltage ΔU, by 90°. Since in the generator X >> r, the value of the current is determined by the formula:

$$I = \frac{E-U}{X} = \frac{\Delta U}{X}$$

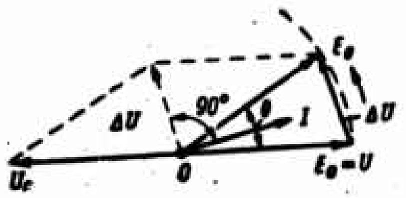

Fig. 4.5. Vector diagram of the conversion of the synchronous generator from the idling operating conditions to a load.

This current almost coincides with respect to phase with the EMF of the generator, and with respect to the power system voltage it is almost in counter-phase, i.e., it is the active current of the load for the generator and the active current for unloading the power system.

If we change the CSD conditions in such a way that the rotor of its generator would have an acceleration with respect to the rotors of the other generators by a certain angle, then the EMF of the generator under examination will be ahead of the EMF of other generators, which will cause a corresponding increase of the active power of this generator. In this way, the leading with respect to phase of the EMF vector of this generator, of the EMF vectors of the other generators, results in an increase of its load, while its lagging results in the decrease.

In order that the generator would yield into the power system only the active capacity, it is necessary to have a certain normal excitation of it, which increases with the increase of the load.

In order to yield to the power system an active and an inductive capacity, the generator should have a certain overexcitation, and in order to yield into the power system the active and capacitative power, it should have a certain underexcitation. The value of overexcitation or underexcitation required, is determined by the value and nature of the load.

5. Work of the Generator in Parallel with the Power System During Variable Excitation and Constant Active Power. (i_B = var; P = const).

In fig. 4.6 we show the vector diagram of a synchronous generator, operating in parallel with the power system of infinite capacity with a variable excitation and constant active power.

Let us trace in the vector diagram the variations of the generator's operating conditions upon the regulation of the excitation current.

With a constant rotating moment of the CSD the active and electromagnetic powers of the generator are constant.

Since the voltage at the generator's terminals remains also constant U = const, then

$$I_a = I \cos \phi = \text{const}, \quad E_0 \sin \theta = \text{const}.$$

The equations show, that vectors I and E_0 have holograph (geometric loci of the ends of vectors) in the form of straight lines cd and ab, shown with a broken line, where three vector diagrams correspond to various EMF value (that is, excitation currents).

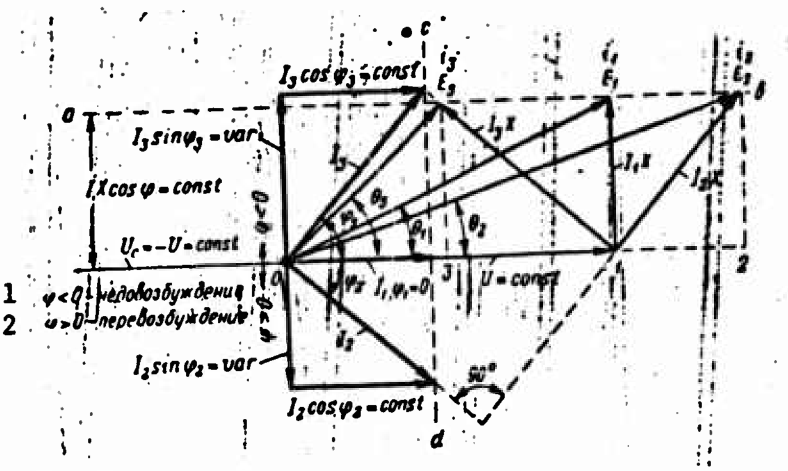

Fig. 4.6. Vector diagram of a synchronous generator operating in parallel with a power system of infinite capacity during excitation variation.
Key: 1. underexcitation, 2. overexcitation.

During normal excitation i_1, the generator has an EMF E_1, $\phi_1 = 0$, minimum possible stator current I_1, and yields into the power system only the active power P.

If we overexcite the generator, in part imparting to it excitation i_2, the values and directions of the EMF E_2 and current I_2, change accordingly; the latter forms angle $\phi_2>0$, with voltage U. The generator gives into the power system the same value of the active power and reactive power of the inductive nature.

An analogous phenomenon occurs upon underexcitation of the generator, when the excitation current i_3, EMF E_3, and current I_3, and angle $\phi_3<0$.

The generator yields to the power system an active power of the same value, and the reactive power of the capacitance character.

In this way the change in the excitation causes a change in the generator current with respect to value, and also with respect to phase through the reactive component, while the active component remains constant.

In fig. 4.7 we show U shaped curves of a synchronous generator, characterizing the work of the machine with a constant power (P = const) and variable excitation (i_B = var.).

The family of curves is given for the various powers $P_3>P_2>P_1>P_0 = 0$, where curve $P_0 = 0$ is taken for the idle running. The minimum generator currents are with $\cos \phi = 1$. With the increase of the power the summits of the curves move upwards and to the right, since upon the increase of the load in order to obtain a constant voltage, the excitation will be increased.

The value of the synchronous resistance of the machine X, has an effect on the character of U-shaped curves, i.e., the smaller the X, the more pointed the curves.

The work of the generator is determined by the boundary straight lines ab and cd, which establish the maximum, permissible stator and excitation currents. For example, with power P_1 the generator may operate without overheating from point 4 to point 5, in this case $\cos \phi$ will differ. After point 4, the stator armature winding will overheat, and right at point 5, the rotor winding (excitation) will overheat.

According to regulation of the excitation current i_B angle θ also changes. The greater the i_B current, the greater the angle θ, and vice versa.

6. Parallel Work of Generators of Comparable Power.

Parallel work of two generators of a comparable power repeating with constant angular velocities in principle occurs similarly to the parallel work of the generators with a power supply line of an infinite

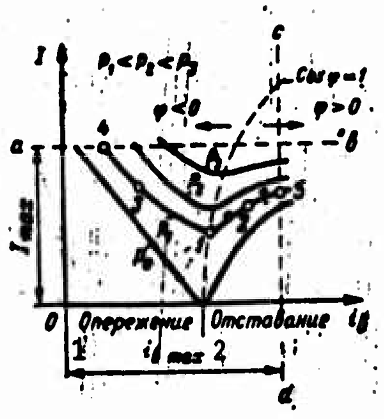

Fig. 4.7. U-shaped curves of a synchronous generator.
Key: 1. lead; 2. lag.

capacity. However, upon the change of angle θ, the voltage vector U, does not remain constant, as it was during the work of a generator with a power system of infinite capacity.

The transfer of a load from one generator to another is qualitatively represented in fig. 4.8. The electromagnetic power developed by the first generator, is determined by angle θ_1, and that of the second by θ_2. If we impart to the second generator a certain lead, $\Delta\theta_2$, then its electromotive force E_2 will move into position of E'_2, and voltage vector U into the position of U', and the current vector I into I' position.

Thereafter, the powers yielded by the generators, are determined by angles θ'_1 and θ'_2. The power of the first generator decreases and that of the second increases.

Upon an increase of the load in the power system in diagram of fig. 4.9, the vectors of I and voltage U will respectively move into positions I' and U'. The active powers yielded by the generators to the power system will be determined by angles θ'_1 and θ'_2. The current vector I' in this case will grow, while the voltage in vector U' will wane. In order to leave the power system voltage unchanged, it is necessary to increase the excitation of the two generators accordingly.

During parallel work of several similar generators their total capacity is approximately proportional to the sum of sines θ, and is distributed between them proportionally to the sines of these angles.

To transfer a load from one group of generators to another, it is necessary to act on the regulators of their drives, which assure the required changes of angle θ in such a way that the sum of angles of one group is equal to the sum of degrees of angles of the other.

Fig. 4.8. Vector diagram of transfer of a load from one generator to another.

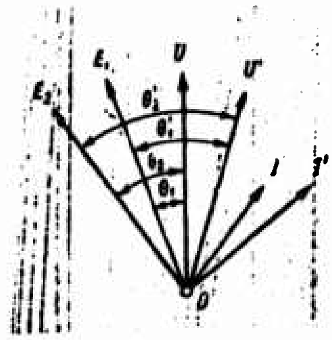

Fig. 4.9. Vector diagram of increased generator load.

The reactive capacity between identical parallel operating generators with equal excitation is distributed equally, which assures the least loads in the copper of the armatures.

The transfer of the reactive load from one generator group onto the other, maintaining the voltage at the busbars unchanged, is reached by changing the excitation of the machine (by decreasing the excitation of the loaded and increasing those of the unloaded).

If it is necessary to disconnect one generator from the power system, we should first transfer from it unto the other generators, the active load and then the reactive current. After this, the disconnection of the generator will not cause a current shock in the remaining generators and voltage oscillations on the power system's busbars.

7. Distribution of the Reactive Power during Parallel Work of Synchronous Generators.

The voltage on the distributing busbars is maintained constant (within permissible limits) with voltage regulators, by changing the excitation of the generators.

Since in actual practice there is a difference of characteristics, tune-up, and speed of the voltage regulators, the overexcitation of some generators and underexcitation of others is possible. As a result of this, the reactive load is distributed between the generators unstably and non-uniformly. This may result in an inpermissible overload of overexcited generators with reactive current.

The reactive power meters (RPM) reacting to the non-uniform distribution of the reactive load, act on the excitation circuits of the generators to voltage regulators and aid in avoiding the above mentioned phenomenon.

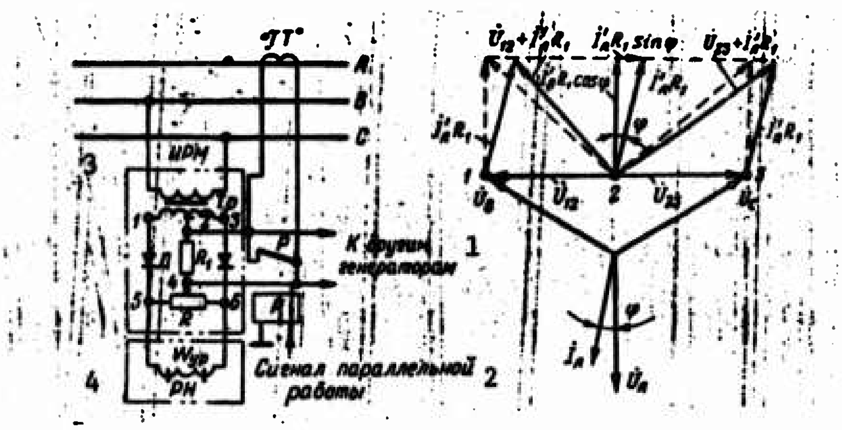

Fig. 4.10. Circuit and vector diagram of the reactive capacity meter.
Key: 1. to other generators, 2. parallel work signals, 3. reactive power meter, 4. voltage regulator.

THE REACTIVE POWER METER (RPM). One of the possible circuit diagrams and vector diagrams of the reactive power meter are shown in fig. 4.10.

The system uses the principle of separation of the signal, proportional to the reactive current of the generator. This signal is sent to the equalizing winding W_{yp} of the magnetic amplifier of the voltage regulator. This device is supplied with power from the input transformer TR connected to the line voltage of the generator. The current generator TT is connected to the "free" phase, and its load is resistance R_1, connected between the mean point of the secondary winding of the input transformer and the output resistance R.

In the diagram we use a one-half period rectification, during which the output voltage is equal to the difference between voltages of the arms of resistor R, and the currents are directed against one another.

When the generators work separately, then the secondary winding of the current transformer TT is shorted by the conducts of relay P, or during parallel work and uniform load of the generators the current from the transformer does not flow through resistance R_1 and the difference of the potentials between points 5 and 6 is equal to zero.

Under a non-uniform load of the generators on the resistance R_1 from the current of phase A (I'_A is the current in which allowances are made for the transformation coefficient) a voltage drop occurs, which is added up with the voltages U_{12} and U_{23} and produces vectors $I'_AR_1 + U_{12}$ and $I'_AR_1 + U_{23}$.

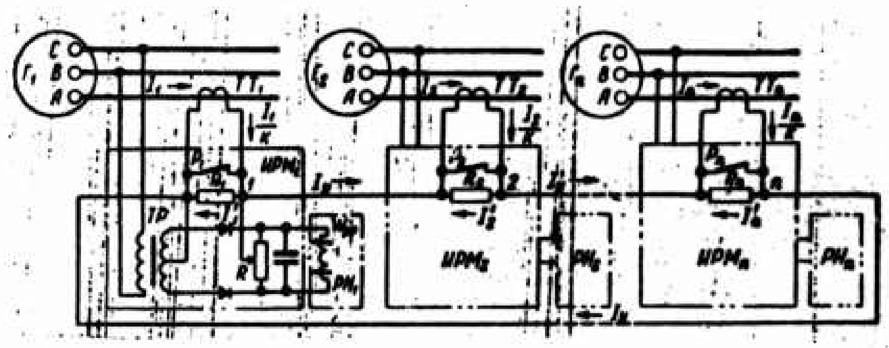

Fig. 4.11. Simplified circuit diagram of the reactive power meters during the parallel work of generators.

If vector $I'_A R_1$ is expanded into active $I'_A R_1 \cos \phi$, and reactive $I'_A R_1 \sin \phi$ components, then the active component upon being added up with vectors U_{12} and U_{23} yields to identical vectors (broken lines on the diagrams) and the difference of potentials of point 5 and 6 from these vectors will be equal to zero. The reactive component is subtracted from vector U_{12} and is added up with vector U_{23}, therefore, between points 5 and 6 there will be a difference of potentials $2KI'_A R_1 \sin \phi$ (where K is the rectification coefficient), proportional to the reactive component of the current.

The difference in the potentials causes a current in the equalizing winding of the voltage regulator. With a lagging cos ϕ in the generator, the ampere coils of the equalizing winding are directed according to the ampere coils of the regulator control winding. In this case the generator voltage decreases proportionally to the value of the inductive current of the imbalance between generators.

With a leading cos ϕ (capacity load) the equalizing current does not change its direction, and the voltage of the generator increases.

DISTRIBUTION OF THE REACTIVE POWER. In fig. 4.11 we present the simplified diagram of the connections of reactive power meters (RPM) during parallel work of n generators, where the secondary windings of the current transformers are connected in series.

If all the generators operating in parallel carry a uniform load, then over the secondary windings of the current transformers flow equal currents proportional to the generator currents. These currents are closed through the equalizing circuit; the voltage drop at the coupling impedances from the reactive components of the current load does not arise, and therefore the loads do not affect the voltage regulators.

If for some reason the reactive load of one of the generators becomes larger than that of the others, then in the coupling impedances the corresponding currents I'_1; I'_2; ... I'_n, begin to flow.

For a circuit, consisting of coupling impedances R_1; R_2; ... R_n (ignoring the resistances of the connecting conductors) according to the second law of Kirchhoff, we can arrive at the following equation:

$$I'_1 R_1 + I'_2 R_2 + \ldots + I'_n R_n = 0. \qquad (1)$$

Where $R_1 = R_2 = \ldots = R_n = R$, to $I'_1 + I'_2 + \ldots + I'_n = 0$.

According to the first law of Kirchhoff for units of 1, 2, ... n, the following expressions are correct:

$$I'_1 = \frac{I_1}{K} - I_y;\ I'_2 = \frac{I_2}{K} - I_y;\ \ldots\ I'_n = \frac{I_n}{K} - I_y \qquad (2)$$

where I_i - is the load current of the i generator;

K - is the transformation coefficient of the current transformer;

I_y - is the equalizing current in the connecting conductor.

Let us substitute these expressions into formula (1)

$$\frac{I_1}{K} - I_y + \frac{I_2}{K} - I_y + \ldots + \frac{I_n}{K} - I_y = 0$$

$$KI_y = \frac{I_1 + I_2 + \ldots + I_n}{n} = I_{cp};$$

$$I_y = \frac{I_{cp}}{K};$$

$$I'_1 = \frac{I_1}{K} - \frac{I_{cp}}{K} = \frac{I_1 - I_{cp}}{K};\quad I'_2 = \frac{I_2 - I_{cp}}{K};$$

$$\ldots I'_n = \frac{I_n - I_{cp}}{K};$$

$$I'_i = \frac{I_i - I_{cp}}{K}.$$

In this way, the current flowing through the equalizing resistance of the i circuit is proportional to the deviation of the load current of the i generator from the mean value of the load currents of all the generators. As it was noted above, the RPM takes from the coupling impedance a signal. proportional to the reactive load, and transmits it to the i voltage regulator. The latter causes a decrease of the excitation current of this generator and a corresponding decrease of its reactive load.

The total voltage drop at all the resistances of the remaining generators is equal to the voltage drop at the resistance of the i generator, but has the opposite sign and is divided between these resistances proportionally to their values. These voltage drops cause a corresponding increase in the excitation current and accordingly of the reactive load of the remaining generators.

In this way we achieve the uniform distribution of the reactive load between the generators, the voltage at the busbars remaining constant.

If, according to the operating conditions or as the result of a fault, one of the generators is disconnected from the common busbars, its current transformer is automatically shunted by plug-contacts of the corresponding relay, eliminating in this way its influence on the distribution of the reactive load between the generators operating in parallel.

FAULTS DURING PARALLEL WORK OF THE GENERATORS may cause the following phenomena:

1. Under excitation of one of the generators owing to the fault or incorrect initial setting of the voltage regulator results in the corresponding reduction of the reactive power load of this generator. The equalizing circuit, striving to level off the reactive load, decreases the voltage at the generators which are in good order. As a result the lower the voltage is established in the power system. During a considerable load on the power system, a large reduction of the synchronizing moment of the faulty generator may result in its falling out of synchronism.

2. Overexcitation of one of the generators due to a fault or incorrect initial setting of the voltage regulator results in a corresponding overload of the same generator with reactive current. The equalizing circuit, striving to level off the reactive load, results in the growth of the voltage on the generators in good order. The voltage at the faulty generator is not decreased because of the faultiness of its excitation. As a result, in the power system there may be established a considerable over voltage, and in this case the faulty generator is overexcited and the ones in good order are underexcited. When there is a considerable load in the power system, the decrease of the generators in good operating order cause them to drop out in synchronism because of the decrease of synchronizing moments.

8. Distribution of the Active Power during Parallel Work of Synchronous Generators.

During parallel work of synchronous generators the active power is distributed uniformly by the automatic system, consisting of active power meters, which correct the devices and the speed regulators, which act on the constant speed drives, which accordingly change the rotating moments of the generators.

ACTIVE POWER METERS (APM). One of the possible systems for an active power meter and its vector diagram with a uniform phase load are presented in fig. 4.12 and fig. 4.13. The system enables us to obtain a voltage, proportional to the active component of the current generator. As we can see from the diagram, the voltage of phase A is divided in half at point 3 and each half U_{13} and U_{32} are rectified by diodes D_1 and D_2 respectively, and mutually subtracted at resistance R_1.

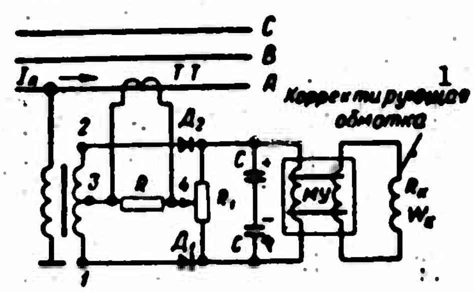

Fig. 4.12. Active Power Meter. Key: 1. corrective winding.

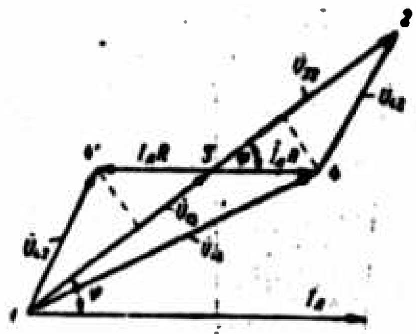

Fig. 4.13. Vector diagram of the active power meter.

Consequently, the resulting voltage taken from this resistance, is porportional to the difference between the vectors of voltages U_{14} and U_{42}:

$$\dot{U}_a = K(\dot{U}_{14} - \dot{U}_{42}),$$

where K - is the proportionality coefficient.

Since voltage U_{14} and U_{42} during the idle run are equal and go in opposite directions, the resulting voltage $U_a = 0$.

If to the resistance R we deliver a voltage proportional to the load current I_a from the transformer current TT, then the voltages U_{14} and U_{42} will be equal respectively to the sum and difference of voltage vectors ($U_{14.0}$, $U_{42.0}$) during idling and voltage drop in resistance R, i.e.:

$$\dot{U}_{14} = \dot{U}_{14.0} + RI_A; \quad \dot{U}_{42} = \dot{U}_{42.0} - RI_A,$$

where the current transformation coefficient is conventionally assumed to be the unity. Now the voltage difference $U_{14}-U_{42}$ is already unequal to zero:

$$U_a = K(U_{14}-U_{42}) = K(\dot{U}_{14.0} + R\dot{I}_A - \dot{U}_{42.0} + R\dot{I}_A) = 2KR\dot{I}_A.$$

With a small $R\dot{I}_A$ value the difference between the voltage vectors U_{14} and U_{42} may be replaced with the difference of their projection on the direction of voltage U_{12}, i.e.,

$$U_a = 2KRI_A \cos \phi.$$

In this way, on the resistance R_1 the output voltage is proportional to the active current of the load. This voltage is used to ascertain the correcting winding of the speed regulator.

DISTRIBUTION OF THE ACTIVE POWER. The drive speed regulator, on receiving the signal from the centrifugal sensor (or Tacho-generator) connected with the generator shaft, and acting on the constant speed drive, provides for the constancy of the speed of the generators' rotations (frequency of the current generator) during both the separate and parallel work of the generators.

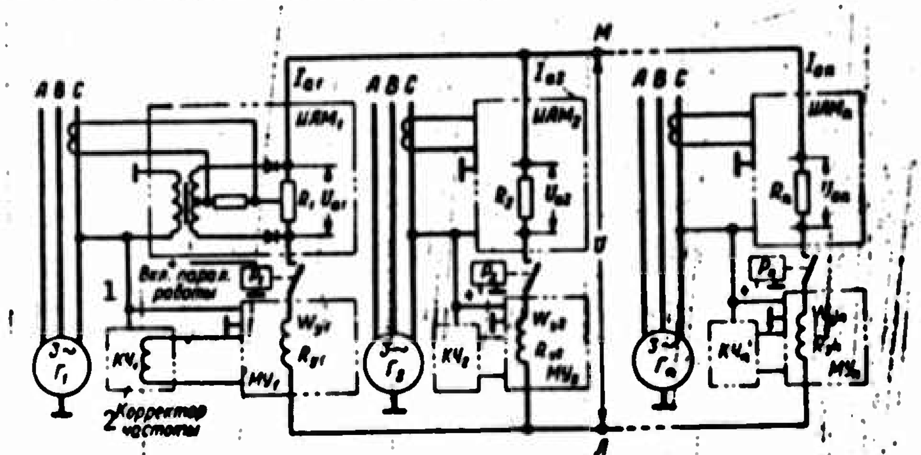

Fig. 4.14. Simplified circuit diagram of the active parallel meters during the parallel work of the synchronous generators.
Key: 1. connected for parallel work, 2. frequency corrector.

The active power meters by means of the correcting windings, acting on the speed regulators, assure the parallel work of the generators and uniform distribution of the active power between them.

One of the possible systems of distribution of active power between the generators operating in parallel is given in fig. 4.14. In the system, the correcting circuits of all the generators are connected in parallel and the resistances of the correcting windings of the magnetic amplifiers are equal, i. e.,

$$R_{y1} = R_{y2} = \ldots = R_{yi} = \ldots = R_{y\,n} = R_y.$$

Let us designate the voltage between points M and L with U on the basis of the first of Kirchhoff's law for point M we can write

$$I_{a1} + I_{a2} + \ldots + I_{ai} + \ldots + I_{an} = 0;$$

$$\frac{U - U_{a1}}{R_y} + \frac{U - U_{a2}}{R_y} + \ldots + \frac{U - U_{ai}}{R_y} + \ldots + \frac{U - U_{an}}{R_y} = 0;$$

$$U = \frac{U_{a1} + U_{a2} + \ldots + U_{ai} + \ldots + U_{an}}{n} = U_{min}.$$

In this way, the voltage between points M and L is equal to the arithmetical mean of the voltage drops at the output resistances of the APM.

If the active load on all the generators is equal and the active components of the load currents and consequently the voltages at the output of the active power meters, will be equal, i.e.,

$$U_{a1} = U_{a2} = \ldots = U_{ai} = \ldots = U_{an} = U.$$

In this case

$$I_{a1} = \frac{U - U_{a1}}{R_y} = 0;\ I_{a2} = \frac{U - U_{a2}}{R_y} = 0;\ \ldots\ I_{an} = \frac{U - U_{an}}{R_y} = 0,$$

i.e., $I_{a1} = I_{a2} = \ldots = I_{a\,i} = \ldots = I_{a\,n} = 0.$

Thus, with a uniform distribution of the active load no currents form in the corrective circuits, consequently, the signal does not arrive to the frequency corrector and the latter does not affect the speed regulator.

If for some reason the active load of one or several generators change, then their correcting voltages (U_{a1}, U_{a2},...$U_{a\ n}$) of all the generators change accordingly. In the corrective windings of the magnetic amplifiers currents originate which are proportional to the deviations of the corrective voltages from the mean voltage value U_{min}: (U_{cp} = U_{min})

$$I_{a1}=\frac{U_{a1}-U_{cp}}{R_y};\quad I_{a2}=\frac{U_{a2}-U_{cp}}{R_y};\ldots I_{a\,n}=\frac{U_{a\,n}-U_{cp}}{R_y}$$

In accordance with these currents the magnetic amplifier, through the frequency correctors, act on the speed regulators in proportion to the deviation of the active load of the generators from the mean active load per one generator.

Thus, for example, if the active load in one of the generators decreases, in its correcting winding then, a current I_{ai} > 0 appears, which will result in an increase of the rotating moment on the shaft of the generator and a corresponding increase of its active power. Simultaneously, in the correcting windings of the remaining generators, inverse direction currents will appear (due to the decrease of the mean value of the correcting voltage U_{min} caused by the decrease of voltage U_{ai}) which will result in a decrease of the rotating moments and active loads of these generators.

9. Automatic Frequency Regulation.

Constant speed drives with speed regulators without a correcting device enable us to obtain a frequency with a precision of ± 2%, but for the automatic synchronization of the generators during parallel work it is required to have a high frequency precision of ± 1% and higher.

In order to obtain a frequency with this precision, usually the differential automatic frequency regulators are used (AFR) with magnetic amplifiers, one of the variations of which is given in fig. 4.15.

The system has two resonance circuits of which one is tuned up for a frequency somewhat more than the rated frequency, and 2, for a frequency somewhat higher than rated. The voltages at the output circuits through rectifiers are delivered in opposite directions towards the regulating winding of the magnetic amplifier.

With the generator frequency equal to the rated, in the circuits' flow currents, shifted with respect to one another by 180°.The potentials at points A and B are equal and consequently, the current at the output is absent.

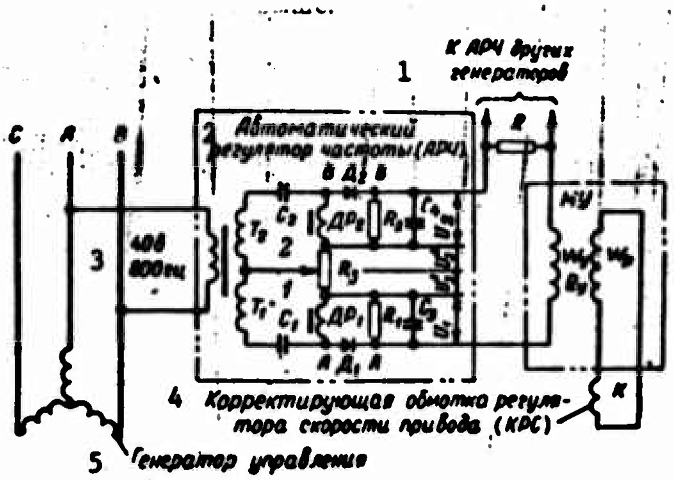

Fig. 4.15. Simplified diagram of automatic frequency regulator. Key: 1. automatic frequency regulator (AFR), 2. to the AFR's of other generators, 3. 40 v 800 cps, 4. correcting winding of the drive's speed regulator (CWR), 5. control generator.

Upon a decrease of frequency the current of circuit 2 decreases, and the current of circuit 1 increases. Consequently, upon the decrease of frequency, the potential of point A will be higher than the potential of point B, and the rectified current will flow from point A to point B over the control winding W_y of the magnetic amplifier.

The value of the current is proportional to the differences of voltage drops at resistances R_1, R_2 and R_3:

$$I_y = \frac{(U_1 + U_3') - (U_2 + U_3'')}{R_y} .$$

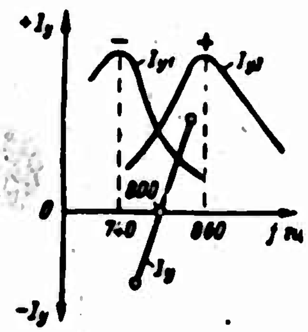

Fig. 4.16. Curve of the current change in the control winding in relation to frequency.

Upon the increase of frequency above the rated, the potential in point B becomes higher than potential in point A, the current in the control winding of the magnetic amplifier will change its direction.

The curve of the current change in the control winding in relation to the frequency change as shown in fig. 4.16, is given.

In order to increase the stability and precision of work of the AFR and decrease of the outside dimensions of the resonance circuits, it is supplied with a voltage of higher frequency (800 or 1200 cps) from the control generator, installed on a single shaft with the principal synchronous generator. The feed from the control generator makes it possible to react to the speed of the rotor's rotation, and not to the frequency of the power supply system, which during transient processes with parallel work might not coincide with the speed of the rotor.

The frequency regulators operating according to the system, maintain the frequency of the synchronous generator with the precision of up to $\pm$ 1% and higher.

With separate and parallel work of the generators, the output circuits of the AFR are connected in parallel as it is shown in fig. 4.17. The diagram enables us to reduce to a minimum the difference in the frequencies of individual generators. From the diagram it is clear, that at the output of each magnetic amplifier, depending on the deviation of the generator's frequency, a voltage is formed.

$$U_i = Kf_i,$$

and in lines connecting points A and B, the mean voltage U_{min} is maintained. Upon the deviation of the frequency of any generator to the control winding W_y, of its magnetic amplifier a current will flow, which is proportional to the instantaneous frequency delineation.

$$I = \frac{U_i - U_{min}}{Z} \equiv \frac{f_i - f_{min}}{Z},$$

where Z - is the resistance of the operating coils of the magnetic amplifier.

In accordance with the control winding current, the magnetic amplifier gives out a signal to the correcting winding of the speed regulator of the drive. The latter changing the speed of revolutions of the generators, restores its rated frequency.

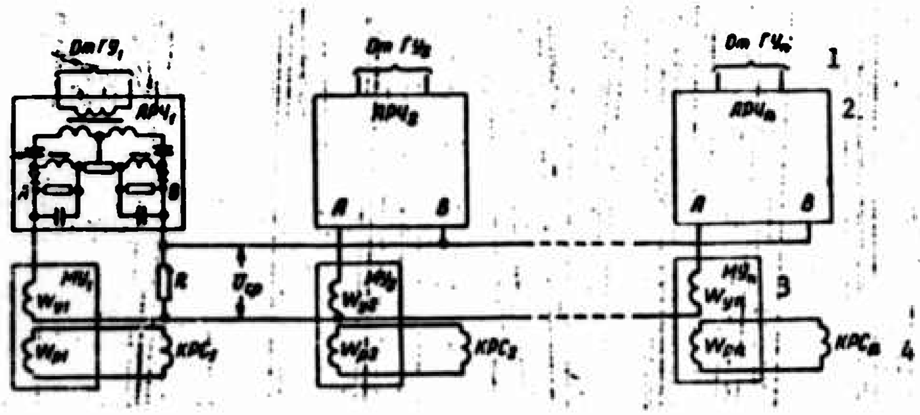

Fig. 4.17. Simplified circuit diagram of an AFR during parallel work. Key: 1. from the control generator, CG, 2. AFR, 3. Ma, 4. CWR.

10. Synchronization of the Generators upon Connection of Parallel Work.

The generators are connected for parallel work with strict synchronization (of voltages, frequencies, phase coincidences, and their identical sequence). The special devices assure the conditions of synchronization at the moment the generator is turned on and maintained after its turn-off under the minimum equalizing current and the minimum excess power shock at the moment of being turned on. Failure to observe the synchronization conditions results in the formation of an equalizing current shock, and an excess moment.

Turning on of generators during equality of voltages and equality of frequencies or non-coordination of phases causes a pulsation of the voltage differences and formation of an active current component, which alternately loads the power supply system and the generator which is being connected with an active power.

Turning on during the equality of frequencies and coincidence of phases but without maintaining the voltage equality, causes an equalization current

$$\dot{I}_{yp} = \frac{\dot{E} - \dot{U}_c}{(R + R_c) + j(X + X_c)}$$

and when $R \ll X$ and $R_c \ll X_c$

$$\dot{I}_{yp} = -j\frac{\dot{E} - \dot{U}_c}{X + X_c},$$

where R and X - are resistances of the generator;
R_c and X_c - are the resistances of the power system,

that is, the equalizing current has mainly a reactive measure. It increases the field of the machine with a lower voltage and decreases the field of a machine with a higher voltage, maintaining an equal voltage at the power supply system's terminals.

Two synchronization methods exist: self-synchronization and precision synchronization. In aviation wide popularity was gained by precision automatic synchronization, the possible simplified diagram of which is given in fig. 4.18.

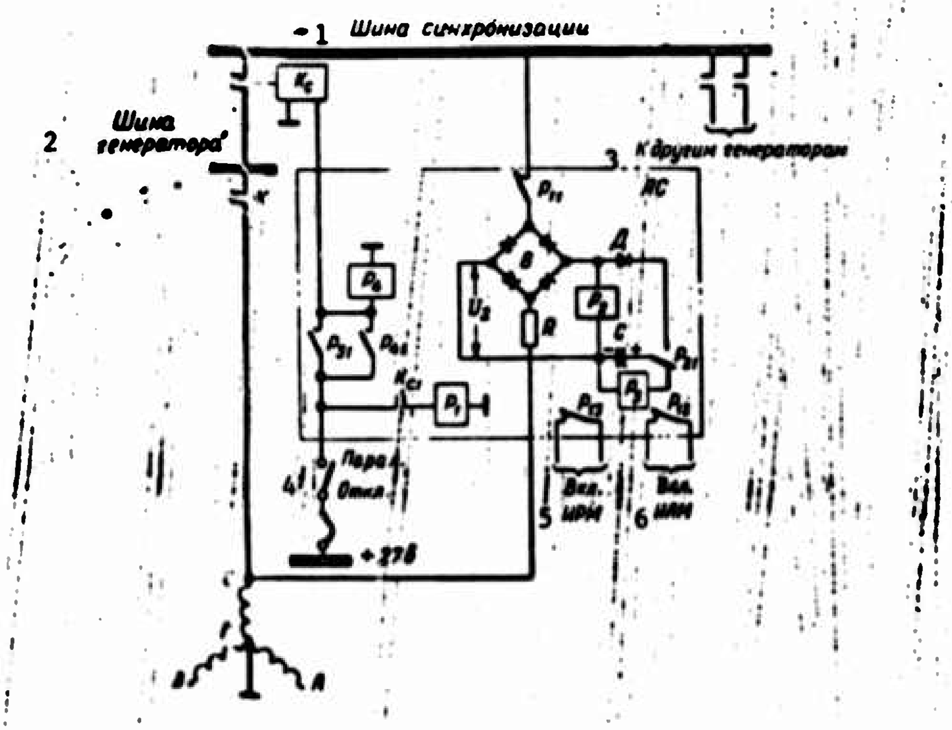

Fig. 4.18. Simplified diagram of the automatic precision synchronization device.
Key: 1. Synchronization busbar, 2. generator's busbar, 3. two other generators, 4. parallel disconnection, 5. turning on the RPM, 6. turning on the APM.

In the system examined, the generator has a frequency close to the power supply system frequency and is connected to its own distributing busbar, with contactor K. The generator is connected for parallel work (to the synchronization busbar) automatically by a synchronizer with the parallel work switch 1 turned on.

To the diagonal of rectifier B, a voltage is delivered equal to the voltage difference of similar phases of the turned on generator and synchronization busbar. This beat-voltage proportional to the slipping of the voltage, is rectified and delivered to the windings of relay P_2. If the rectified voltage U_2 is higher than the voltage required for operating relay P_2, the relay operates, contacts P_{21}, and condenser C begins to charge.

Upon synchronization, the voltage U_2 will drop to a value of release of relay P_2 and contacts of P_{21} will close the circuit of relay P_3 and condenser C will discharge through the winding of relay P_3. Upon the operation of relay P_3 the contacts of P_{31} close. Contactor K_c operates and connects the generator for parallel work (to the synchronization busbar). Contacts K_c close the circuit of relay P_1. Contacts P_{11} open, disconnecting the automatic synchronization AS, from the synchronization busbar, the contacts of P_{12} close and those of P_{13} open, connecting ARM and RPM respectively for parallel work.

In this way the generator is connected to the synchronization busbar (for parallel work) after relay P_2 opens after a certain time equal to the total time of operation of relay P_3 and synchronization contactor K_c.

11. Behavior of the Power System During Faulty Operation of the Drive and Role of the Idling Clutch.

The output shaft of the CSD and the generator shaft may be connected rigidly all through an idling clutch, assuring a one-sided transmission of the rotating moment from the drive to the generator. If the rate of rotation of the generator increases the rate of rotation of the output shaft of the drive, the clutch disengages the shaft, permitting slipping.

If, because of the fault of the drive, the rate of revolution of one of the generators increases considerably, this will result in the following phenomena:

1. The faulty generator is loaded with an active power, i.e., it takes upon itself all the active power of the power supply system, if it is capable of covering it.
2. The faulty generator delivers an active power to the generators in good order, operating as motors.

If the shafts are connected tightly, the power is expanded for rotating the drive. If the shafts are connected by an idling clutch, a small amount of power is used only for overcoming the friction of the slipping clutch.

3. As a result of the excessive overload, the faulty generator may fall out of synchronism, causing great power fluctuations in the system.
4. The equalizing circuit of the active power meters strives to increase the rate of revolution of the generators in good order.

5. The current frequency in the power system increases substantially.

6. The voltage remains unchanged, and the generators in good order deliver their share of reactive power to the power system.

If, because of the fault of the drive, the speed of revolution of one of the generators decreases, the following takes place:

1. The faulty generator discharges its active power.
2. The generators in good order take upon themselves the active power of the faulty generator.
3. Generators in good order deliver active power to the faulty generator, which operates as a motor.

If the shafts are connected tightly, the power is expanded for rotating the drive. If the shafts are connected with an idling clutch, the small amount of power is spent only for overcoming the friction of the slipping clutch.

4. A faulty generator, operating as a motor, continues to deliver to the power system its share of reactive power.
5. Upon a considerable decrease of the speed of the faulty generator's drive, the current frequency in the power system decreases.

In the presence of an idling clutch, the faulty generator should be left connected to the power system, since it draws only a small active power for slipping of the clutch, at the same time working as the reactive power compensator.

Chapter V. PROTECTION AND CONTROL OF SYNCHRONOUS GENERATORS.

1. General Statements.

With certain types of damage to the generator and its feeder line, the rise and drop of voltage and frequency beyond the power of permissible values is possible.

During short-circuits inside the generator or in its feeder, the current-bumps may exceed ten-times the rated value and inspite of their brief duration, may produce difficult conditions for the generator itself and the elements of the electric-energy transmission and distribution system connected with it.

The above mentioned phenomena have a substantial influence on the working capacity of the electric power system and consumers and make it necessary to use the corresponding protective devices.

The principal types of protection for a-c generators and their feeders are:

1. Maximum current protection, reacting to the short-circuit current in the circuit protected. The protective system goes into action when the current exceeds the previously established values and operates without a time lag (current cut-off) or with a time lag (maximum protection).

2. Differential current protection from short-circuits, based on the principles of comparison with the currents at the beginning and end of the protective circuit (longitudinal protection) and in two parallel lines with a similar parameter (lateral protection). This protection system operates without a time lag (practically instantaneously) if the difference between the currents compared, exceeds the previously established value.

3. Protection from the minimum and maximum voltage operating with a time lag upon the deviation of the voltage beyond permissible bounds.

4. Protection against decrease or increase of frequency, operating with a time lag upon the deviation of the frequency beyond the permissible limits.

Generator and feeder protection against short-circuits should satisfy the principal requirements demanded of the power supply system's protective devices with respect to selectivity, speed, sensitivity, and reliability.

The maximum current protection may be carried out by means of fuses, bi-metallic automatic devices, or current relays. The other types of protection work may be carried out only by means of relays and are called relay types.

According to the method of action of the fluctuating element on the main conductor of the generator, the relays are divided into direct and indirect action relays. In direct-action relays the fluctuating elements act mechanically on the disconnecting mechanism (latch) of the conductor. In the indirect-action relays, the fluctuating elements control the circuit of the auxiliary source of working current, feeding the disconnecting device of the conductor.

Protective systems with indirect-action relays in comparison with protective systems with direct-action relays, require operating current, have a more complex system, and greater range of operating network, but possess a higher precision, sensitivity, and consume less power, in as much as they control the operating current circuit.

In a-c systems, a certain popularity was gained by indirect-action protective systems, using for operating purposes the a-c power lines or auxiliary transformers and control generators.

When a damaged generator is disconnected from a power system, the delivery of power to the short-circuit location from the remaining generators stops. However, the rotor of the damaged generator continues to rotate, and in the presence of excitation the EMF, induced into the windings of its armature, produce impermissible currents in the place of damage. Therefore, in generators, automatic devices are provided which make it possible to de-excite the machine rapidly.

A magnetic field may be extinguished in the generator by means of short-circuiting the excitation winding, introduction of an active resistance into the excitation, and so forth. The simplest and most widely used method is the break of the generator's excitation circuit.

During all types of dangerous cases of damage, the protective system should send signals for disconnecting the generator's excitation, the power circuit of the generator from the power system and drive, and also for turning on signals about the generator going out of order.

2. A Maximum-Current Relay Protective System.

The maximum-current relay protective system is intended for disconnecting the generator from the power supply system and extinguishing its excitation field in case of a short-circuit at its busbars or feeder, and also for signaling of generator failure.

One of the possible diagrams of the protective system with a current relay T and time relay B is shown in fig. 5.1. In this diagram, the current of transformers TT are connected at the beginning of the stator winding of the generator and its zero point. In this case the protective zone includes the generator's feeder and its busbars. With any type of short-circuit in the zone protected, in the coils of relay T, currents appear proportional to the primary phase currents. The relay operates, disconnects the generator from the power system, extinguishes its excitation field, and delivers a signal to the generator's failure.

The system is equally sensitive to all types of short-circuits, because a full damage current is always directed to a minimum of one of the relays.

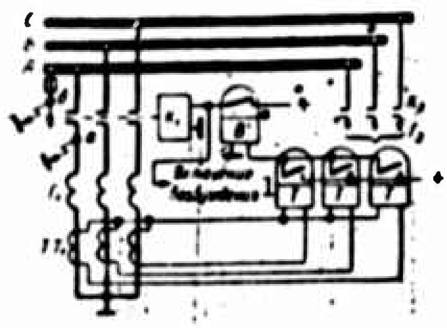

Fig. 5.1. Diagram of the maximum protection of a synchronous generator with an independent time lag.
Key: 1. turning on the exciter.

The short-coming of this system is its relative complexity, caused by the necessity of installing a time relay, current transformers, and current relays at all three phases.

In order to assure the selectivity of the active generator feeder's protective system, during short-circuit, is the consumer's feeder (point b), the time relay should have a time lag greater than the operation of the protective device of any of the consumers, which results in a decrease of the speed of action of the generator. This protection of a generator's feeders may find employment in a single-generator power system, with low power consumers and a rapid protective system.

We should bear in mind, that in the two-generator system, such a protection will act non-selectively, during short-circuits in the generators' feeders. For example, in point a, near to the busbars, since the currents of both generators will be practically similar. Therefore the generator with feeder in good order may be disconnected first, and then the generator with the damaged feeder and the system will be deprived of current.

The working capacity of a power supply system in this case may be restored by means of a repeated automatic switching-on of the generators after the short period of time, suggested above. In this case it is obvious that the generator with a closed feeder will not be switched on, in as much as its voltage cannot be restored. But introduction of a repeated switching will make the protective system even more complicated, and in actual practice it will stop to react to alternating short-circuits.

3. Longitudinal Differential Current Protection.

In order to isolate a broken down generator from the power system and prevent the further development of the consequences of the short-circuiting of the generator or its feeder a rapid action longitudinal differential current protection is used, two variations of the circuits of which are given in fig. 5.2.

Into each of the synchronous generators' phases transformers are connected in series, one at each side of the armature's winding.

Under normal operating conditions of the generator (see fig. 5.2,a) through the maximum-current relay P flows the difference between currents i_2 and i'_2 of the secondary windings of the current transformers. With identical transformers the current difference is equal to zero. The identity of transformers is an important condition, excluding the imbalance of currents i_2 and i'_2, and false operation of the protective system.

During a through short-circuit outside the protection zone (at point 1) in the primary transformer windings, flow currents of the short-circuit i_{sc} of a single direction. In this case relay P does not operate, since

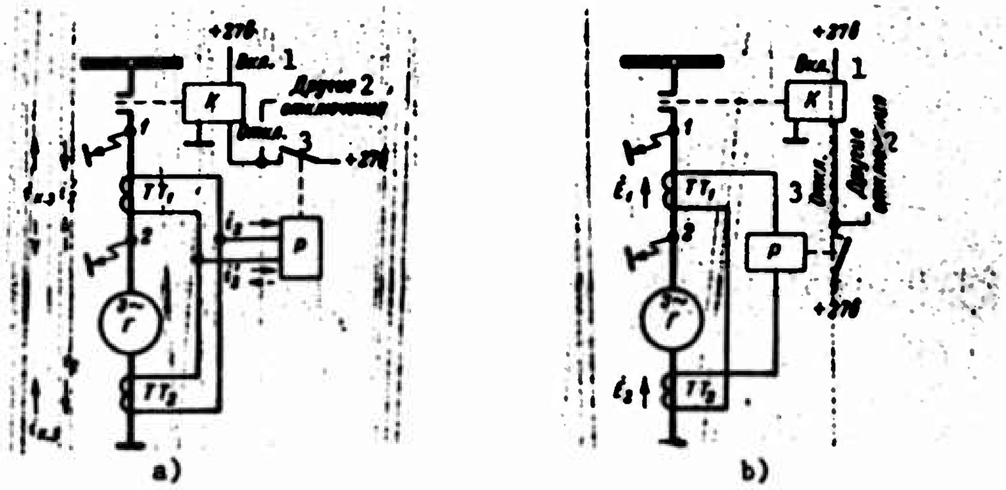

Fig. 5.2. Diagrams of a longitudinal differential current protective system for synchronous generators (single-line picture): a-c with circulating currents; b-c with balanced voltages.
Key: 1. connection, 2. other disconnections, 3. disconnection.

the difference between currents i_2 and i'_2 is equal to zero.

During a short-circuit in the protective zone (point 2) the primary windings of the transformers flow short-circuit currents of different directions, that is, the phase of the current of one of the transformers changes by 180°. To relay P flows the sum of currents i_2 and i'_2. The relay operates and instantaneously disconnects the excitation, the drive, and the generator from the power system and turns on signals on the generator's failure.

The system of the differential current protection with balanced voltages (see fig. 5.2,b) the secondary windings of the TT of each phase are interconnected in such a way, that with identical initial currents the EMF of the secondary windings are directed against each other. The winding of the current relay is connected in series with the secondary windings of the transformers. The current in the relay coils will be equal to

$$\dot{i}_p = \frac{\dot{E}_1 - \dot{E}_2}{Z_B},$$

where $\dot{E}_1$, $\dot{E}_2$ - are the EMF of the secondary windings of TT;

Z_B - is the full resistance of the secondary circuit, including the resistances of the conductors, relay winding, and secondary windings of the TT.

Under normal operating conditions, or with a short-circuit outside of the protected zone, $\dot{E}_1 = \dot{E}_2$, $I_p = 0$, and the relay does not operate. With the short-circuit in the protected zone, $\dot{E}_1 \neq \dot{E}_2$ and in the relay current will appear, greater than the operation current ($I_p > I_{p.op}$), the relay operates and disconnects the damaged generator.

The differential current protective system is selective and does not require coordination with the protective systems with other sectors of the power system. In distinction from the maximum current protective system the differential system does not require a time lag to assure selectivity of its action, and is made rapid-action, due to which it reacts not only to metallic, but also to intermittent short-circuits.

The protection operation current I_{po} should be equal to or less than the minimum short-circuit current in the protective zone, i.e.,

$$I_{po} < I_{s.p.min}.$$

Usually, $I_{po} \approx 0.5\ I_{s.p.min} \approx 0.5\ I_{s.p.min\ gen}$, since the minimum short-circuit current takes place during a single sided supply of the system's busbars, only from the given generator.

The protective system should operate with external short-circuits and abnormal operating conditions. This means, that the current for relay operation should be greater than the imbalance current I_{ds}, which flows through the relay under the above mentioned conditions and is caused by the dissimilar characteristics of the transformers' TT.

The decrease of the imbalance currents is reached by a high degree of identity of the current transformer characteristics, and also by the use of saturated TT.

The longitudinal differential protection of the three-phase generator and its feeder may be three-system, which may be made by means of a three-current relay (one for each phase), six current transformers, and six auxiliary conductors. This protection reacts to all types of short-circuits in the feeder and generator, with the exception of short-circuiting loops in the armature's winding. However, the most rational method is the use of a simple one-system circuit diagram using 1 relay and 2 combined transformers (summators) which sum up the currents of three phases and make it possible to obtain single-phase currents or voltages, used for operating the relay.

4. Protection During Emergency Deviation of the Voltage and Frequency.

In fig. 5.3 we give a diagram of the a-c generator protection against over-voltage, made with semi-conductor instruments. The action of the system is based on the properties of silicone supporting diodes (stabilitrons) ST_1 and ST_2, with a certain value of reverse voltage. We know, that the inverse current of the diode is very small (several μA) until the reverse voltage in it reaches the voltage for operating it, after which the current passing through the diode increases sharply and is limited only by the circuit's resistance. This property of the diode makes it possible to use it as an element determining the level of the voltage for operating the protective device.

The time lag before operation of the output electromagnetic relay P is provided by means of capacitor C_1.

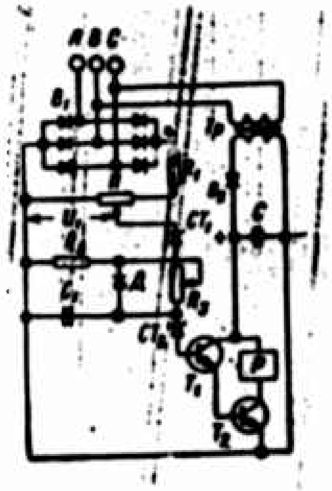

Fig. 5.3. System of protection against over voltage.

Under a normal generator voltage the rectified voltage U_1, supplying the relay circuit, is lower than the voltage for opening diode ST_1. Condenser C_1 in this case is practically discharged through choke coil D and resistance R_2. The required minimum voltage for operating the protective system is established with potentiometer Po. When an over voltage occurs the U_1 voltage becomes greater than the voltage required for opening diode ST_1. The latter is opened and through its condenser C_1 is charged. The time for charging the condenser to a certain prescribed voltage is determined by the time constant of the condenser's circuit ($\tau = C_1R_3$) and the over voltage value.

When the voltage on the condenser reaches the point required for opening diode ST_2, the latter is opened and produces a signal for the two-cascade amplifier, made with semi-conductor triodes T_1 and T_2 of the n-p-n type. At the amplifier's output a relay P is connected, which operates in the presence of an over voltage as the power supply system. The amplifier is supplied with power from the generator through transformer GR and rectifier B_2.

Rheostat R_e may change the time required for charging condenser C_1 to a voltage sufficient for opening diode ST_2, i.e., it can change the time required for operating the protective device under a given over voltage value. With an unchanged resistance R_3 the time required for charging the capacitor will be inversely proportional to the over voltage, i.e., the relay has a dropping volt-second operation characteristic.

With brief over voltages in the power supply system, the capacitor C_1 has not enough time to be charged and the primary relay does not operate.

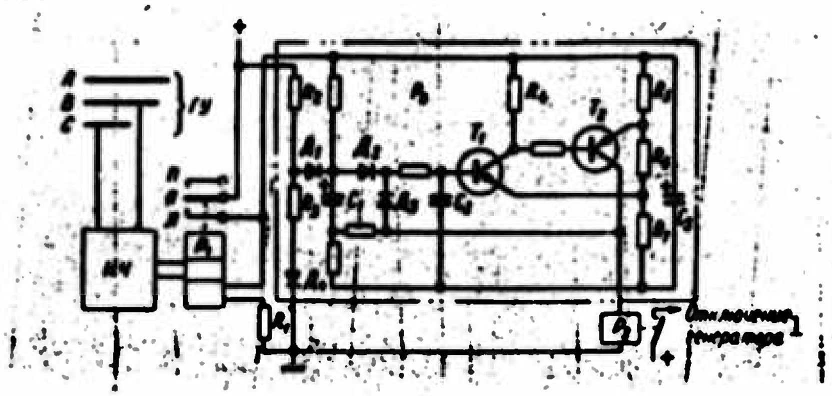

Fig. 5.4. System for protection against a frequency rise.
Key: 1. disconnection of the generator.

Upon the disappearance of the over voltage the capacitor is rapidly discharged through diode D and resistance R_2. The resistance R_1 serves for the temperature compensation.

The operating principle of the protection against an emergency voltage drop is analogous to the one examined above. When the generator reaches the minimum permissible voltage, relay P operates and remains under a current during the normal operating conditions. The relay is released upon a decrease in the voltage and disconnects the corresponding generator and feeder line.

PROTECTION AGAINST A RISE IN FREQUENCY serves for disconnecting the generator from the power system upon deviation of its frequency beyond permissible limits. The protective system consists of a frequency meter (FM) a polarized relay P_1, time relay P_B, and output relay P_2 as shown in fig. 5.4.

The generator's frequency is controlled by the frequency meter FM with a double resonance contour, the operating principle of which is analogous to the operating principle of the frequency meter in the system of automatic regulation in the drive speed. The difference consists in the tune-up of the circuits in the working apparatus. The working apparatus : polarized relay P_1, which upon an increase in frequency operates and supplies power to the time relay R_B. In order to eliminate the "bell" working conditions in the zone of operation of relay B_1, and operative feed-back R_1 is used, which decreases the return coefficient.

The time relay P_B consists of a static device, which uses circuit RC and transistors T_1 and T_2.

When relay P_1 operates, the voltage is delivered to relay P_B, the capacitors C_1 and C_2 begin to charge and when the potential of the transistor T_1 exceeds the potentiometer, the transistor opens. In this case the drop in voltage at the resistor R_4 creates a negative displacement on the base of transistor T_2. The transistor opens, relay P_2 operates, and sends a signal for disconnecting the generator from the power system.

In order to assure the relay nature of the time relay characteristic in it, we use the positive feed-back through diode D_3. In order that no inverse polarity voltage would appear on capacitor C_1, it is imparted the constant displacement from the separator R_2R_3 through diode D_4. To the emitter of transistor T_2 we send a displacement by the divider R_5, R_6, and R_7.

PROTECTION AGAINST FREQUENCY LOWERING operates analogously to the protection against frequency rise, relay P_1 under the rated frequency being under voltage, and being released upon the lowering of the frequency below the permissible level. In this case the intermediate relay (which is not shown in the diagram) operates and turns on the time relay. After a certain time lag, relay P_2 sends a signal for disconnecting the generator.

5. Principles of Construction of Protection and Control Systems for Generators.

The systems for protection and control of the sources of electric energy are interconnected, and have elements, which establish a certain logical dependence between the input and output signals. For this purpose the logical elements "end", "or", "not", and their combinations, are used. The diagrams of the logical elements are shown in fig. 5.5.

Each logical element may have several input and output signals. The logical value of the signals is conventionally designated with "1", if the action takes place, and "0" if it does not take place.

THE LOGICAL ELEMENT "END" is called such an element, the output signal from which is taken in the presence of signals at all its inputs. (see fig. 5.5, a). The significance of the output signal in the symbolic record, will have the form of a logical product of values of the input signals:

$$F(U_{out}) = U_1 \cdot U_2 \dots U_n.$$

The output function is equal to 1, if its multipliers are equal to 1 and equal to 0, if anyone of its output values is equal to 0.

In the logical system of element "END" with semi-conductor instruments, we show the triodes of type n-p-n, which open when a positive potential is brought after its base. The output signal $F(U_{out})$ takes place with a closed triode T_1, when the resistance of its emitter-collector transition is maximum. Triode T_1 passes into the closed state when triode T_2 is open, the latter being opened only in the presence of positive signals at all the inputs. If at least one of the signals is smaller than the prescribed value, the base of triode T_2 will be under a voltage of the smallest signal, and it will remain closed, and triode T_1 will be open and $U_{out} = 0$.

LOGICAL ELEMENT "OR" is the name of such an element, the output signal of which is taken in the presence of a signal of at least one of its inputs (see fig. 5.5,b). The value of the output signal in the symbolic record has the form of an algebraic sum:

$$F(U_{out}) = U_1 + U_2 + U_3 + \dots + U_n.$$

The logical sum has a value of 1, when 1 is equal to at least 1 of the components, and value 0 if all the components are equal to 0.

In the logical system of element "OR" made with semi-conductor instruments, the voltage at the output (U_{out}) takes place with a closed diode T_1 and open triode T_2. To open triode T_2 it is sufficient to have a signal at at least one of the inputs.

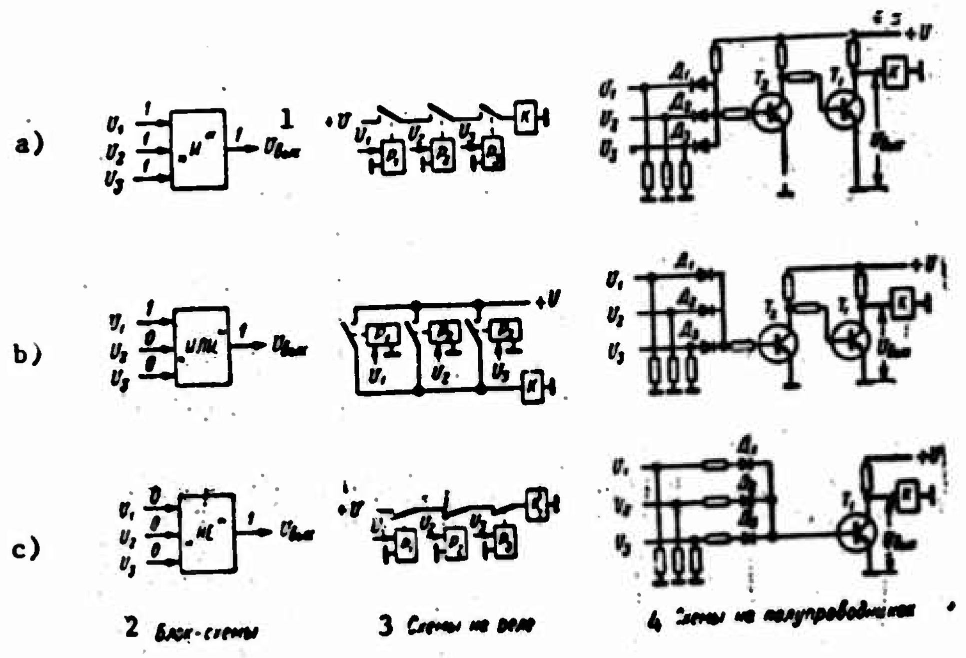

Fig. 5.5. Diagrams of logical elements "END", "OR" and "NOT". Key: 1. U_{out}, 2. simplified diagrams, 3. diagrams with relays, 4. diagrams with semi-conductors.

IN THE LOGICAL ELEMENT "NOT" the output signal takes place only in the absence of signals at all its inputs. (see fig. 5.5,c). The dependence of the output signal on the input signals is symbolically written in the following form:

$$F(U_{out}) = \overline{U}_1 \cdot \overline{U}_2 \dots \overline{U}_n.$$

If the product has a symbol $\overline{U}$, then it has a value of 1, when the signal signals to 0 (U=0) and a value of 0, when the signal is equal to 1.

In the logical diagram of element "NOT" with semi-conductor instruments, the voltage at the output U_{out} remains until the appearance of a signal at one of the inputs.

Let us examine separate simplified diagrams of protection and control of a-c generators, operating in parallel, determining in this case their logical functions and relationships.

The generator should be included in the power system with adherence to the following conditions: the switch is in the "on" position, the voltage and frequency of the generator are rated, the generator's voltage is in phase with the voltage of the power supply system, the over voltage, excess of frequency, short-circuits in the generator and its feeder are absent, and the source of airfield power supply is disconnected from the power system aboard the aircraft. The simplified diagram is shown in fig. 5.6,a.

DURING OVER-VOLTAGE THE PROTECTIVE SYSTEM should disconnect from the power system the faulty generator, extinguish its magnetic field, and not permit a repeated connection of the generator to the power system, until the source causing the over voltage is eliminated. The disconnection takes place under the following conditions: when there is an over-voltage in the power system, when the reactive power yielded by this generator is in excess of the mean value of the reactive power per generator, and when there exists an over-voltage condition above a specific time. The circuit diagram is given in fig. 5.6, b. The irreversibility of operation of the protective system against over voltage is shown in the system with a feed-back.

PROTECTION DURING A LOSS OF EXCITATION, if it is not caused by the decrease of the rate of revolution, disconnects the generator from the power system irreversibly. The disconnection takes place when the voltage is below a specific value; the reactive power yielded by this generator is lower than the average, per one generator; the rate of revolutions of the generator (frequency) is not lower than its specific value and the lengths of the excitation loss conditions exceeds a prescribed time. The circuit diagram is shown in fig. 5.6,c.

PROTECTION AGAINST A FREQUENCY EXCESS disconnects irreversibly the generator from the power system and shuts off the excess of air or hydraulic fluid to the drive in order to prevent the run-a-way speed of the rotating parts. The disconnection occurs when the frequency exceeds the permissible limits; the active power yielded by this generator, is above the active power per one generator; and the length of the distance of an excessive frequency, then conditions are longer than permitted. The simplified circuit diagram is shown in fig. 5.6,d.

PROTECTION AGAINST FREQUENCY DROP should produce a reversible signal for disconnecting the generator, since a decrease of frequency is possible with normal operating conditions (lifting of the aircraft engine). The disconnection takes place under the following conditions: when the frequency drops below the permissible value; the active power, given up by the generator is below the mean active power per one generator; the length of the existence of the lower frequency condition exceeds the prescribed time of lag. The simplified diagram is shown in fig. 5.6, e.

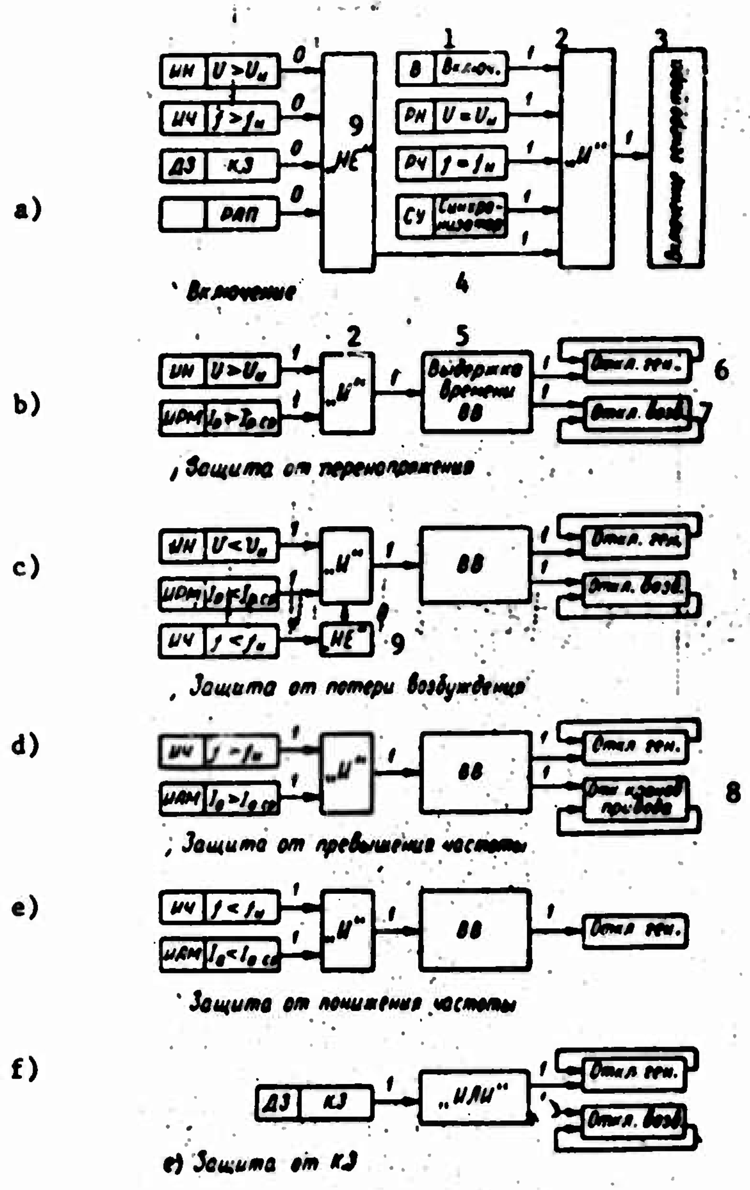

Fig. 5.6. Simplified diagrams of control and protection of generators.

Key: 1. on, 2. or, 3. connection of generator, 4. synchronizer, 5. time lag, 6. generator disconnected, 7. exciter disconnected, 8. drive valves turned off, 9. "NOT", "END", "OR". a) turning on, b) protection against over voltage, c) protection against excitation loss, d) protection against frequency excess, e) protection against frequency drop, f) protection against short-circuit.

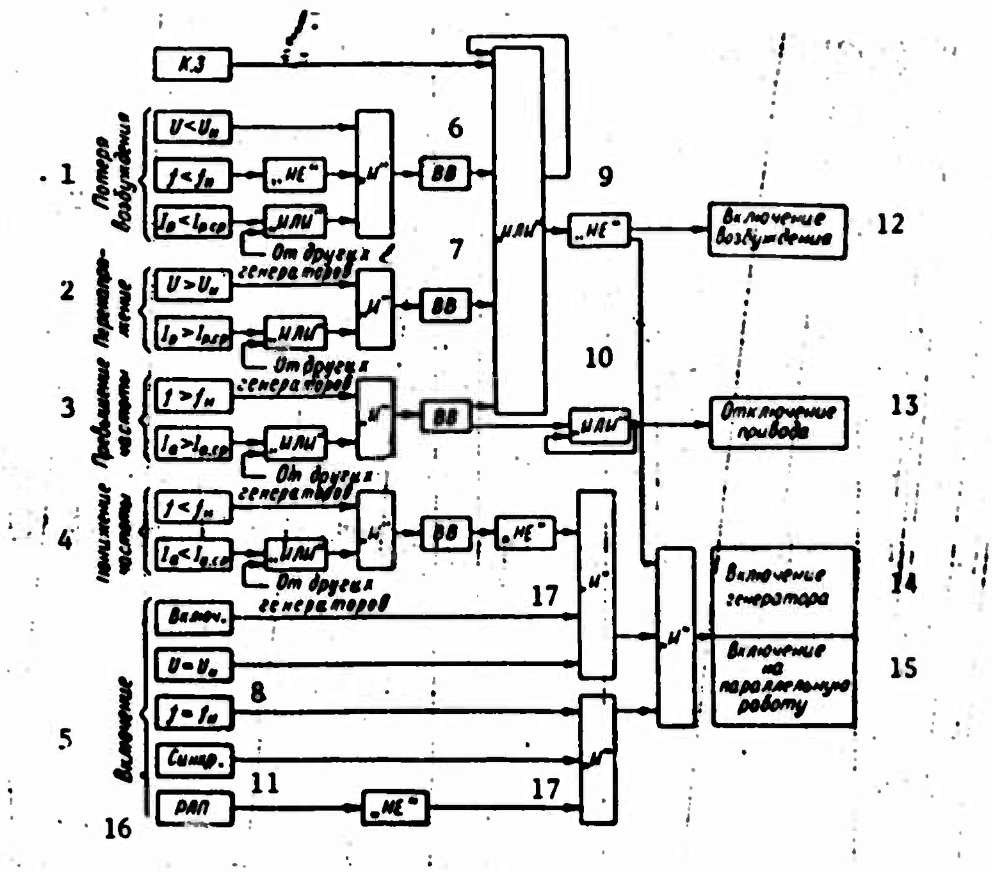

Fig. 5.7. General simplified diagram of control and protection of generators.
Key: 1. excitation loss, 2. over voltage, 3. frequency excess, 4. frequency drop, 5. connection, 6. time lag, 7. from other generators, 8. on, 9. "NOT", 10. "OR", 11. synchronizer, 12. excitation on, 13. drive of, 14. generator on, 15. connection for parallel work, 16. automatic starting relay, 17. "END".

WITH PROTECTION AGAINST SHORT-CIRCUITS inside the generator or its feeder line, the generator is irreversibly disconnected from the power system without a time lag. The simplified diagram is shown if fig. 5.6, f.

On the basis of the above examined individual simplified diagrams we construct an general simplified diagram for the protection and regulation of generators (fig. 5.7). As it follows from the elimination of the diagrams not all the protective systems cause irreversible disconnection of the generator. Therefore, the outputs from irreversible protective systems are delivered not to the power conductors, but at the input of the logical element "OR" from which the signals are taken for disconnecting the generator, its excitation, and to the clogging input.

In developing a common control and protection system, it is possible to reduce considerably the required number of instruments of the same type, since the same logical elements may be used both for the control system and for the installed protective system. In the logical elements for END, which use diodes, because of the considerable value of the reverse current, it is necessary to have more than three inputs. When necessary, the parallel connection of the "END" elements is used.

Chapter VI. Diagrams of Primary A-C Power Systems.

1. Diagrams of Control and Protection of Electric Power Systems.

In a-c power systems the principal idea of raising the reliability consists of the division of each system into two independent parts, each of which may carry out all the functions of the system, as a whole. Under normal conditions both parts of the system work simultaneously. In this way, in case 1 sub-system goes completely out of order, the remaining one continues to supply all the consumers, providing a high degree of probability of completion of the flight. Elements already tested in operation are used as much as possible in the systems.

Below we examine circuit diagrams of the power systems of three-phase alternating current with voltage of 200/115 v of a-c and d-c frequency with 2, 3, and 4 generators. The principles applied in these systems may be extended to power systems with any number of generators.

The principal part of the a-c energy is used without transformation for feeding three-phase and one-phase consumers, a part of it is transformed with respect to voltage to 36 and 28 v, and a certain share is transformed into direct current with a 28 v voltage, by means of the transformer-rectifier units.

Generators of three-phase alternating-current with a grounded power neutral, have become widely used as a primary energy source. For control, regulation, and protection, we use equipment of the static type, using magnetic amplifiers and semi-conductor elements, the systems of which were examined earlier.

The speed of revolutions of the generators are maintained constant mainly by means of the differential hydraulic and pneumatic drives, with a constant speed, with a reverse regulation system. In power systems, protection against short-circuits, breaks, and deviations of parameters beyond permissible limits is provided for. Moreover, provisions are made for the possibility of disconnection of the conductor and generator from the aircraft engine by means of the disconnection clutch, controlled from the cockpit, upon the formation of dangerous faults. It is possible to connect them back again only on the ground.

In the majority of cases in the power systems, provisions are made for an emergency generator of a three-phase alternating-current driven by an auxiliary power unit. The emergency generator is used only to supply power to vitally important consumers when all the main generators have failed during flight. Generators driven by the auxiliary power unit, in some cases are connected during the take-off to increase the reliability of electric power supply or to economize the thrust of the principal aircraft engines. They are used also on the ground when the aircraft engines are not operating.

The power system aboard the aircraft is supplied on the ground with a three-phase alternating current from an airfield source through a connecting rose. In this case all the sources aboard are automatically disconnected from the power system independently of the position of their switches. A ground source is connected to the power system aboard the aircraft only in the case when the frequency, voltage, and sequence of its phases are within permissible limits.

In fig. 6.1 we show a typical diagram of synchronization control (using signal lamps) and control of the principal parameters of the power systems (by means of a frequency meter, voltage meter, and Wattmeter). The parameter control instruments are switched over from one generator to the other by the package switch. The Wattmeter normally shows the active power, and when the button is pressed it shows the reactive power. According to the indications of the Wattmeter, observations are made on the distribution of the active and reactive powers between generators.

The operating conditions of the generators and their drives are prescribed by setting up the switches in a corresponding position: separate, parallel, and grouped. After this, the further control, regulation, protection and observation of the power systems' work is carried out automatically. Upon the deviations of the power systems' operating conditions from the prescribed, the corresponding signal-lamps light up.

In the primary power system diagrams we show the most rational methods of connecting secondary energy sources - voltage transformers VT, static convertors SC, and transformer-rectifier units TRU. The static convertors of direct-current into three-phase alternating-current are used as emergency sources when the principal power system fails.

In fig. 6.2 we give a typical diagram of control and protection of an a-c power system. Each generator with conductor K_1 - K_4, is connected to the corresponding main-busbar MB, which in turn may be connected during parallel operation through the synchronizing conductors

K_g to the synchronizing busbar ShS in a starter circuit (see fig. 5.1, section 4).

The field damping conductor K_{gp} is connected by briefly pressing a switch V_1 to the "on" position, and K_{gp} operates, then is disconnected. When switch V_1 is closed, a short pulse to magnetize the exciter is fed through the circuit V_1-VP_3-K_{gp1}.

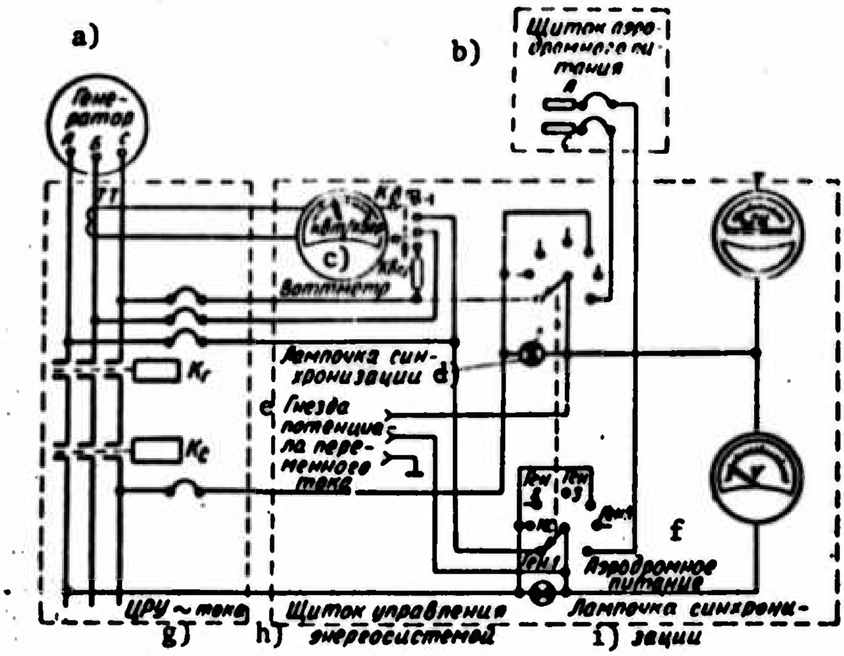

Fig. 6.1. Diagram of instruments in a-c systems. Key: a) generator, b) airfield supply panel, c) Wattmeter, d) synchronization lamp, e) a-c potential plug, f) airfield supply, g) TSRU-current, h) power system control panel, i) synchronization lamp.

Briefly pressing switch V_1 to the "off" position disconnects K_{gp1}. When K_{gp1} is disconnected, its contacts in the supply circuit of the disconnecting electromagnet of conduct K_1 are closed, so that main conductor K_1 is disconnected immediately after disconnection of K_{gp1}.

Cutout switch V_2 is used to control conduct K_1; normally this switch is in the "on" position, in which the generator is automatically connected and disconnected. When the generator is connected to the idled circuit, the power on the winding of the connecting electromagnet is fed through switch V_2, the conducts of conductors K_2- K_4 (remaining generators disconnected), through the contacts of the minimum speed relay, the contacts of the minimum voltage relay (the relay operates at a voltage near the nominal), and contacts of conductor K_r

The generator is connected for parallel operation using the synchronizer, the contacts R_s of which stunt the contacts of the main contactors of the remaining generators. The synchronizer is connected to the voltage difference of the generator and ShS synchronizing busbar. Each generator includes an individual synchronizer.

With minimum operating speed, the contacts of the centrifugal disconnector TSV are opened, disconnecting the relay R_n; this relay closes its contact to the circuit of the winding of the disconnecting electromagnet for conduct K_1 and the generator is disconnected from the line.

The circuit has the following types of protection:

1. Longitudinal differential current protection from short-circuits in the feeder and within the generator using three current transformers TT_1 (in each phase), three current transformers TT_2 and three relays R_d (see diagram, fig. 5.2). When short-circuits occur within the zone of protection, one relay R_d closes and feeds voltage to the disconnecting electromagnet K_{gp1}, which causes the generator field to be damp and disconnected from the line.
2. Protection from overexcitation of the generator through three-phase over-voltage relay $R_u>$ (see diagram, fig. 5.3).
3. Protection from loss of excitation through three-phase minimum voltage relay $R_u <$ This relay is disconnected when voltage 0.9 U_{nom} arises, and has a time delay for relief of contacts to eliminate false operation during short-voltage drops.
4. Protection from phase interruption before connection of the generator into the line is performed using minimum voltage relays, and after connection of the line using the zero sequence current filter.
5. Protection from back active power using the back power relay. This protection is used in rare cases.
6. Protection from excessive increase in exciter voltage using the thermal relay (bimetallic relay), providing the necessary time delay. The relay returns automatically.
7. Protection from short-circuits in generator busses with a back sequence voltage filter.

Reliable power supply to the control circuit and generator protection from three sources of current are provided:

- from the 27 v d-c;
- from the a-c generator through transformer f and rectifier device VP;
- from the generator exciter. When there is no power from the first two sources, relay R_{rp} is disconnected and closes its contacts in the sub-exciter feed circuit.

The circuit for control of generators and ground power supply is assembled so that when one generator is connected, the ground power supply is disconnected. Actually, when the generator begins rotating and is excited, the normally open relays of these contacts will close in the circuit of the disconnecting electromagnet's winding of conductor K_p and it is turned off. At the same time, the normally open contacts of the relays will open in the circuit of the turning-on electromagnet winding of conductor K_p, which excludes the possibility of turning the latter on.

The system of control and protection of the power systems' supply which were examined, is applicable with a separate work of the generators, but in this case instead of equipment for parallel work, we introduce an equipment for automatic switching over of the busbars, when individual generators fail (see paragraph 2).

In fig. 6.2 we show the circuit diagrams of the voltage regulator VR and frequency regulator FR, with voltage meters VM, reactive power meters RPM, frequency meters FM, and active power meters APM included in them and the corresponding connections with the exciter frequency corrector.

2. A-C Power System with an Unstable Frequency.

In fig. 6.3 we present the diagram of a three-phase a-c power system with a voltage of 200/115 v with unstable frequency. The energy sources are two generators of three-phase alternating-current, which are powered by the aircraft engines.

The generators operate separately each for a certain group of consumers. Under normal conditions the G_2 generator delivers energy to busbar E, and generator G_1 to busbar D and emergency busbar F.

Busbar D provides the power supply to a number of consumers, including the transformer-rectifier unit TRU_1, which transforms the alternating current into a direct-current with a voltage of 28 v.

Busbar E supplies a number of consumers, including the 200/28 v transformers, delivering energy to busbar J, from which the lighting equipment receives its feed.

From the emergency busbar F, feed is delivered to the vitally important consumers, including the emergency TRU_2.

Upon an increase or decrease of the voltage at the terminals of anyone generator above the permissible limits, its distributing busbar automatically switches over to the generator in good order and in the crew's cockpit, a signal lamp lights up indicating which of the generators is not working.

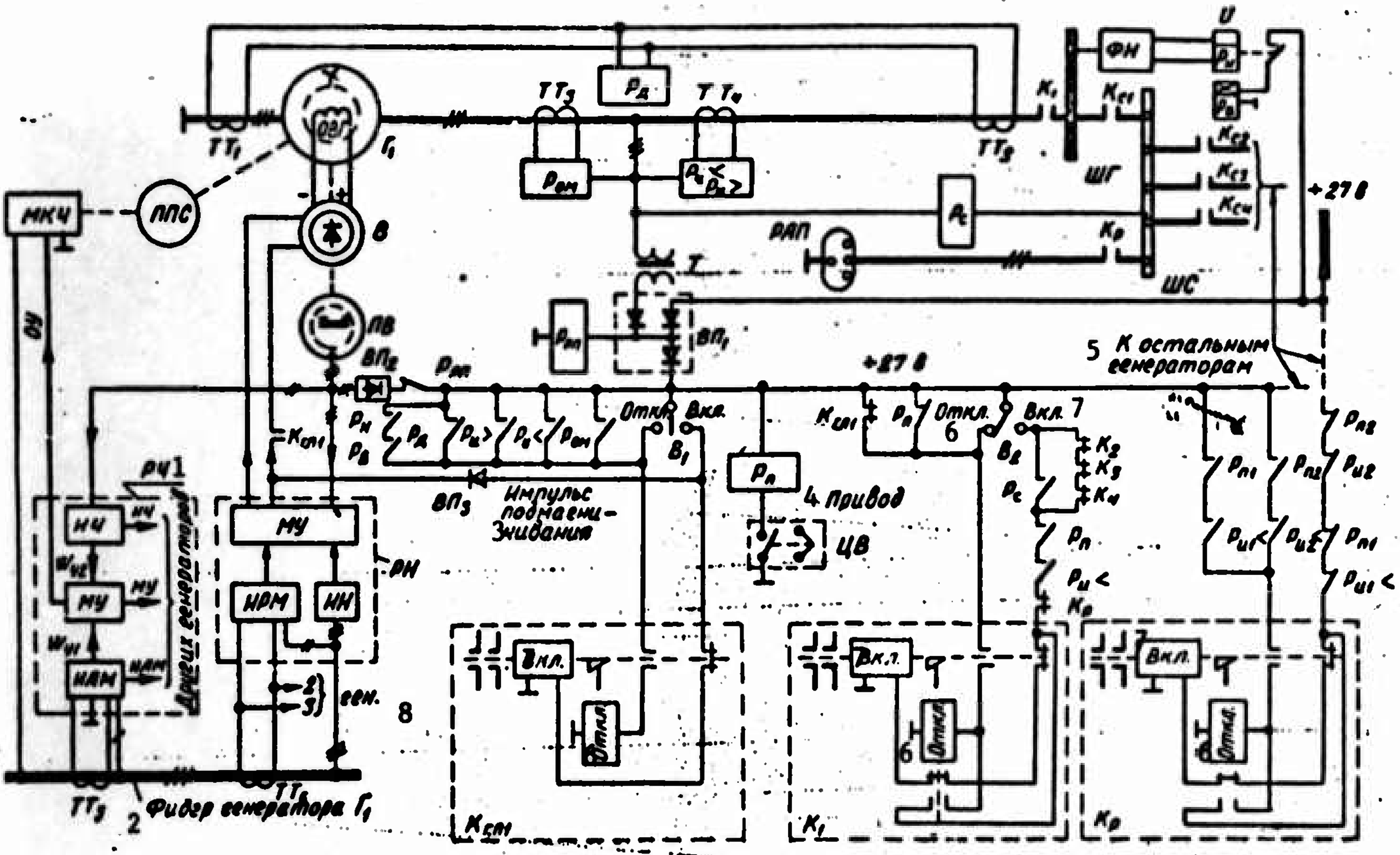

Fig. 6.2. Typical diagram of protection and control of an a-c power system: CSD - constant speed drive; G_1 - generator; GEW - generator excitation winding; E - exciter; SB - sub-exciter; VR - voltage meter; APM - active power meter; FF - frequency meter; FR - frequency regulator; FCM - frequency correction mechanism; CS - centrifugal switch; P_n - minimum revolution relay; K_{gp1} - field extinguishing conductor; K_1 - generator's main conductor; K_r - conductor of the airfield rose; K_{c1} - K_{c4} - synchronization conductors; K_2, K_3, K_4 - auxiliary contacts of the main conductors of the remaining generators; TT_1-TT_6 - current transformers; R_d - current relay of longitudinal differential protection against short-circuits; T - step-down transformer; P_c - synchronization relay; $P_u<$ - minimum voltage relay; $P_u>$ - over voltage relay; $P_{u2}<$, $P_{u3}<$, $P_{u4}<$ - contacts of minimum voltage relays of the other generators; P_{om} - reverse power relay; P_{rn} - relay for connecting the reserve feed of the control circuits from the exciter; $ВП_1$, $ВП_2$ - rectifiers; $ВП_3$ - valve rectifier; B_1 - pressure switch of the field extinguishing conductor; B_2 - generator control switch; ФН - reverse sequence voltage

filter; P_n - voltage relay; P_B - relay with time lag for closing the contacts.

Key:
1. Other Oscillators
2. Feeder of Oscillators 1
3. Pulse magnitization
4. Leed
5. To other oscillators
6. Disconnect
7. Connect
8. Oscillators

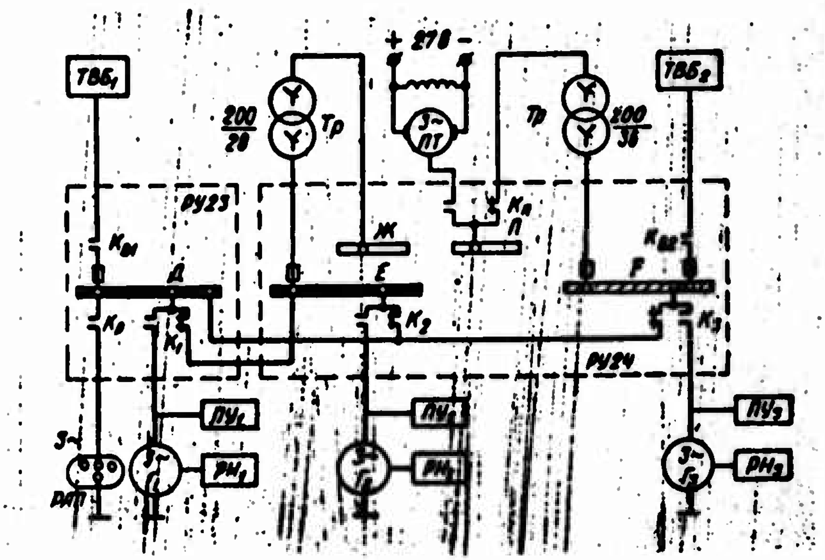

Fig. 6.3. Diagram of an a-c electric power system with unstable frequency (single-line picture): G - generator; K, K_n, K_B, K_p - conductors of the generator, converter, rectifier, rose; VR - voltage regulator; CP - control panel; AFR - airfield feed rose; TRU - transformer-rectifier unit; TC - three-phase converter; TR - transformer.

The electric power supply system has minimum frequency relays, which upon the decrease of the rpm of the engine below 65% of the rated speed, disconnect the busbars from the corresponding generator and these are automatically connected to the generator in good order.

If the generators are installed on a single aircraft engine, all the consumers stop their work with the exception of those which serve the aircraft engine. These consumers can operate when the rpm are reduced to 40%.

When both generators fail, the emergency busbar F receives feed from the emergency a-c generator, driven by an air-vane, which in this case set outside to be operated by the oncoming stream of air. From the busbars F, the instrument feed busbar I, and the emergency rectifier TRU_2 receive their feed.

During normal work the pilot's instruments receive their power supply in the form of a-c, 36 v, and frequency of 400 cps from the convertors. When the convertor fails, they automatically connect to feed from busbars F through the transformer.

The airfield power supply is connected to the power system aboard the aircraft through a terminal rose, all the distributing busbars being automatically disconnected from the shipboard generators and connected to the ground power source. The convertor is also disconnected while the instruments receive their power supply from busbar F through the transformer.

The power system provides a reliably supply of power to a-c consumers. The quality of energy with respect to frequency is best under the rated rpm of the engine and is maintained within permissible limits in a small range of the engine's rpm.

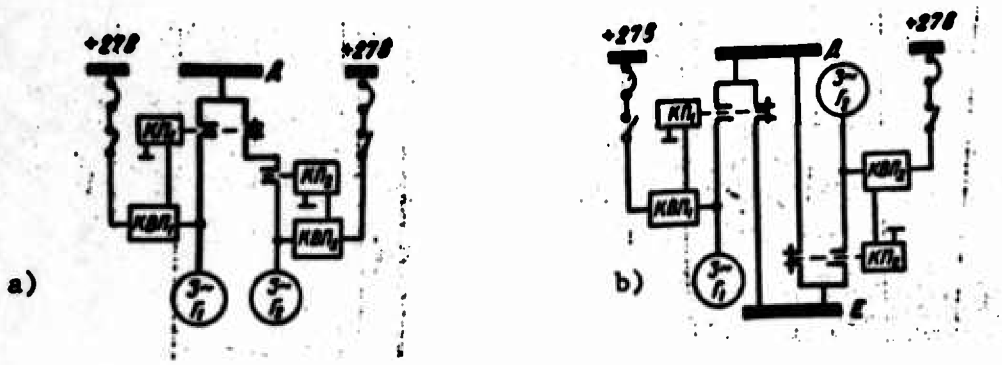

Fig. 6.4. Diagrams of automatic reservation of the consumers' feed in two-generator systems.

The power systems with two generators are useable on aircrafts with one or two engines. However, it may be successfully used also on aircraft with several engines, and its reliability will increase with the increase of the number of engines and generators.

From the facts examined above, it follows, that the generators which receive feed directly from aircraft engines, operate in a-c power systems separately. In order to assure the uninterrupted feed to consumers, the power systems are provided with not less than double power supply to the distributing devices' busbars; a 100% reservation of the generator power; automatic connection of reserve generators instead of the main ones gone out of commission, during a minimal short time; the possibility of connecting generators for parallel work under normal conditions and any failures; elimination of generator over load when several of them fail during flight and during successive starting of aircraft engines on the ground.

Let us examine several possible variations of the systems of automatic reservation of the feed to consumers during separate generator operations, which assure solution of the above problems.

In fig. 6.4 we show the systems of automatic reservations of the consumers' feed in systems with two generators.

In diagram a, both switches are normally closed, both generators are excited and conductors КП$_1$ and КП$_2$ are turned on. In this case, generator G_1 is the principal one and it supplies power to the loads while generator G_2 is in stand-by reserve. If for some reason generator G_1 is disconnected, then conductor КП$_1$ with its normally closed conducts will connect the reserve generator to the busbar. The simultaneous connection of the generators to the busbar is impossible here; damage to the circuits of the d-c generator G_1 does not prevent connection of generator G_2.

a)

b)

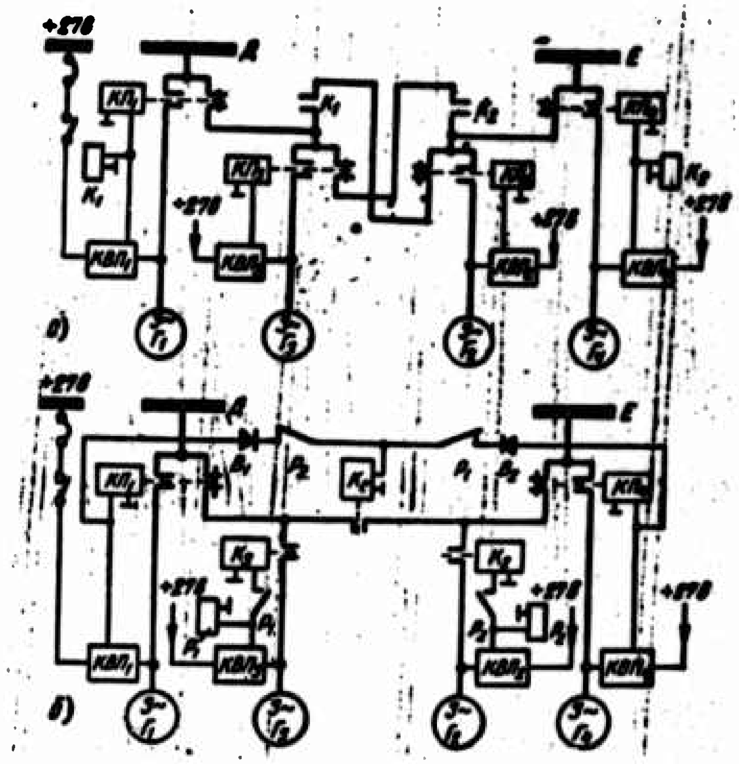

Fig. 6.5. Diagrams of automatic reservation of consumers' feed in four-generator systems.

In system b, the loads are divided between the two busbars D and E. Under normal conditions, the generator G_1 supplies power to busbar D, and generator G_2 to busbar E. When any generator goes out of commission, the corresponding KП is turned off, which results in the combination of both busbars, and their supply is provided for by the remaining generator.

In fig. 6.5 we give diagrams of the automatic reservation of the feed to consumers in four-generator systems, which provide feed for all the consumers, when any one of the two generators goes out of commission.

In diagram a, during the normal work of the system, all the generators are excited, conductors $KП_1$-$KП_4$ and K_1, K_2, are turned on, busbar D receives power from generator G_1, and busbar E from generator G_4, generators G_2 and G_3 are on stand-by. When generator G_1 goes out of commission, busbar D receives its power from generator G_3, and when generators G_1 and G_3 go out of commission, it receives power from generator G_2.

When generator G_4 goes out of commission busbar E receives power from generator G_2, and when generators G_2 and G_4 go out of commission it receives power from generator G_3.

The overloading of reserve generators G_2 and G_3 during simultaneous going out of order of three generators is prevented by conductors K_1 and K_2. For example, when generators G_1, G_2 and G_4 go out of order the generator G_3 supplies only busbar D. The feed circuit of busbar E is interrupted by conductor K_1. Analogously, when generators G_1, G_3, and G_4 go out of commission, generator G_2 supplies only busbar E, while the feed circuit of busbar D is interrupted by conductor K_2.

The generators cannot be connected for parallel work according to this system, thanks to use of switch-over conducts $KП_1$-$KП_4$. The reserve generators are connected independently of the good order of the feed of control circuits of the principal generators. In this way, the system satisfies completely all the principal requirements.

Diagram b is analogous to diagram a, it differs by the smaller number of power switching equipment. The system consists of two groups of generators, with 2 generators in each group. Provisions are made for joining the groups by connecting conductor K_c, the winding of which may receive its power supply over two circuits.

- from $KП_1$ through the logging valve B_1, and normally closed conducts of relay P_2;
- from a $KBП_4$ through the logging valve B_2, and normally closed conducts of relay P_1.

With normal work all the generators are excited, conducts $КП_1$, $КП_4$ K_3, K_2, and relay P_1, and P_2, are connected; conductor K_c is disconnected, busbar D receives its feed from generator G_1 and busbar E from the G_4 generator.

When generator G_1 goes out of commission, the busbar D receives its power from generator G_3, and conductor K_c is disconnected. When generator G_1 and G_3 go out of commission, is the operating generator G_4 through closed contacts of relay P_1, conductor K_c is connected and busbar D receives its feed from generator G_2. If at the same time generators G_1, G_2, and G_4, go out of commission, conductor K_c will not be connected and the generator G_2 will feed only busbar E. Analogously conductor K_c will be turned on when generators G_2 and G_4 go out of commission and the generator G_1 remains in good order, and in this case the generator G_3 will be connected to busbar E. The normally open contacts of relays P_1 and P_2 in the circuits of the windings of conductors K_2 and K_3 exclude brief inclusions of generators G_2 and G_3 for parallel work.

§3. A-C Power System with Separate Work of the Generators.

In fig. 6.6 we present a diagram of the three-phase a-c power system with a voltage of 200/115 v, constant frequency of 400 cps, with separate work of the generators for a specific group of consumers. The source of energy are three three-phase generators, which are powered by constant speed drives.

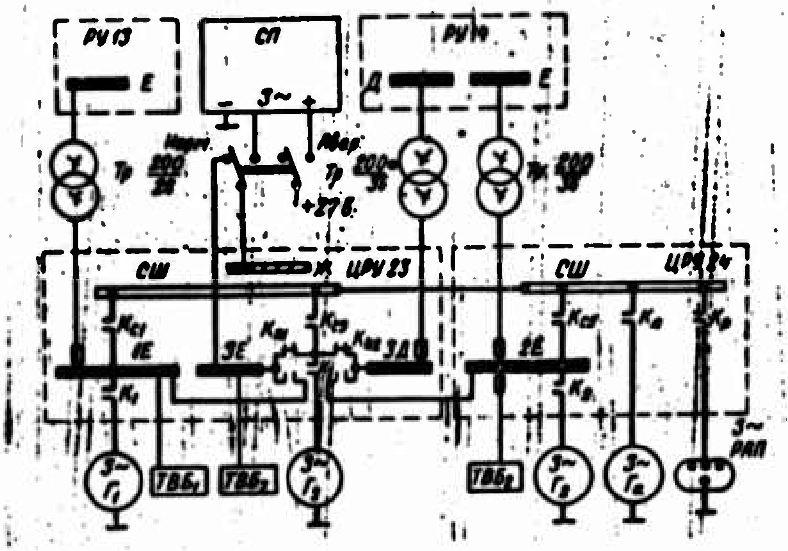

Fig. 6.6. Diagram of an a-c power system with separate work of the generators (unilinear picture).

The emergency feed with three-phase alternating-current is carried out from generator G_a, installed on the auxiliary independent unit, which is started during flight when the principal generators fail. The emergency feed is received from a static convertor of d-c into three-phase a-c. The ground feed with alternating-current is delivered through the airfield ASR contact rose.

The diagrams provide for logs, which do not permit parallel work of the main, emergency, and ground power sources, during any combinations of connections. The voltage decreases from 200 to 36 v and 28 v, by transformers T_r and is delivered to the distributing devices DD13 and DD14.

During normal work generator G_1 supplies power to busbar 1E, generator G_2 to busbar 2E, and generator G_3 to busbar 3E, 3D and emergency J.

The busbar of generator G_3 is divided into two parts 3E and 3D, in order that when one generator goes out of commission, the two others could supply power for all the load, divided approximately in half. The most important duplicating consumers of electric power are divided between busbars 1E and 2E.

Under emergency conditions, the loads are switched over in the following way: When generator G_1 is damaged, conductor K_1 is turned on and its generator is disconnected from the power system. At the same time conductors K_{c1} and K_{c3}, and the switch-over conductor $K_{\Pi 2}$ operate. Busbar 1E is connected with generator G_3 and busbar 3D to generator G_2.

When generator G_2 goes out of commission, conductor K_2 is disconnected, conductors K_{c2} and K_{c3} and switch-over conductor $K_{\Pi 1}$ are switched on. Busbar 2E becomes connected to generator G_3, and busbar 3E to generator G_1.

When generator G_3 is damaged conductor K_3 is turned off, and the conductors $K_{\Pi 1}$ and $K_{\Pi 2}$ are turned off. In this case busbar 3E is connected to generator G_1 and busbar 3D to generator G_2.

When any two generators fail, a-c power supply is provided for busbars 1E and 3E or 3D and 2E. In this case the power supply to the emergency busbar J is always assured; in the first case from busbar 3E and in the second from the static converter. The loads between the busbars are distributed in such a way that upon going out of commission of two generators, the flight might continue under any conditions.

In case of failure of the automatic switch-over systems of the alternating-current, a manual switch-over is provided for which is carried out by three switches. When any one constant speed drive or genenerator goes out of commission the corresponding signal bulb lights up, informing the crew of the damage and indicating which switch should be used for switching over the busbars. The switches are mounted in such a way, that it is impossible to switch over simultaneously more than one switch.

4. A-C Power System with Parallel Work of the Generators.

In fig. 6.7 we present a diagram of the a-c three-power system with a voltage of 200/115 v, constant frequency of 400 cps. The energy sources are for three-phase generators, which are activated by constant speed drives. On the ground the aircraft power system is supplied with three-phase a-c power from an airfield source, by means of contact rose.

The energy from the generators is transmitted to the corresponding generators' busbars into the central distributing systems (CDS) from which it is directly distributed to the consumers and their secondary distributing devices (DD). Conductors K connect the generators to the principal busbars, and conductors K_c connect them for parallel work. In the system provisions are made for parallel work of the generators, however the loads are distributed in such a way that each generator would be able to supply its group of consumers during separate work, but busbars D and E of the secondary DD are connected to the principal busbars, with conductors K_h. In case of a fire which originated because of the faults of the power system, the flight engineer by pressing the common switch board, disconnects simultaneously all the conductors K_h. If after this the source of the fire was not isolated, then the connecting conductors K_c are disconnected and in this way the generators are isolated from one another. Further, depending on the feed generators G_2 and G_3 are separated in sequency and finally generators G_1 and G_4 one by one. In this case the emergency busbars F which supply power to especially important consumers, are under current up to the disconnection of the corresponding generator.

When the switches are turned off, the control and protection of the generator is performed automatically by the control panel (CP) which gives the corresponding signals to the conductors. The generators are connected for parallel, then during emergency conditions the corresponding panel isolates automatically the damaged generator from the general power system and further, depending on the nature of the damage done to it, disconnects it.

§5. The A-C Power System with Two Self-Contained Systems.

The entire three-phase a-c power system with a voltage of 200/115 v with a constant frequency of 400 cps is divided into two self-contained systems. The energy source in it consists of two three-phase a-c gener-

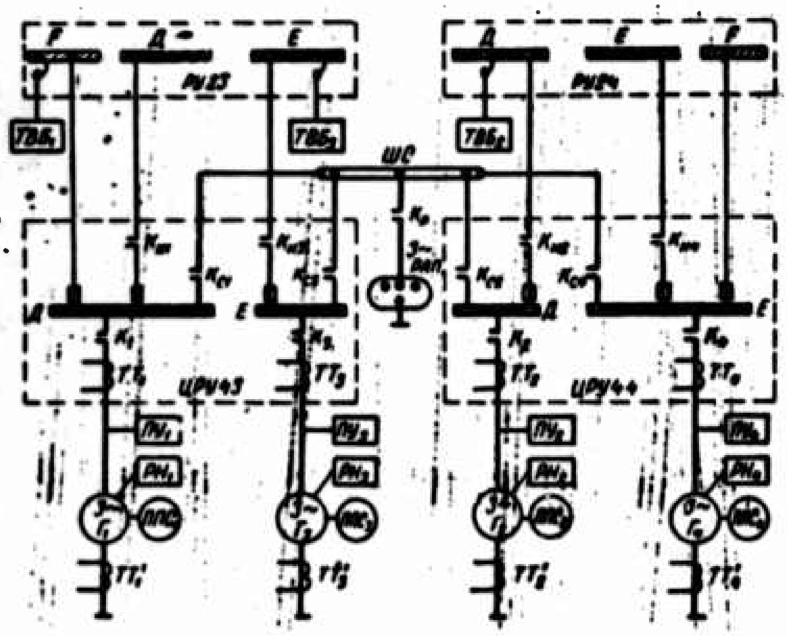

Fig. 6.7. Diagram of an a-c power system with parallel work of the generators (unilinear picture): G - generator; K, K_h, K_c, K_p - are conductors of the generator, load, synchronization, and airfield feed contact rose; VR - voltage regulator; SR - panel for control and protection of the generator; TT and TT' - current transformer of the differential protective system; AFR - airfield feed contact rose; SB - synchronization busbar; TRU - transformer-rectifying unit; CSD - constant speed drive.

ators which are driven by the constant speed drives. The simplified diagram of the power system is given in fig. 6.8. Each generator supplies power to a separate a-c busbar. Most busbars during normal work are isolated from one another, but are automatically connected with one another when one of the generators goes out of commission, and also when the power supply is provided by the generator, driven by the APU or a ground source. Since the power of all the consumers does not exceed 50% of the total power of the generators, one generator provides the normal work of all the consumers.

In order to increase the reliability of an uninterrupted power supply to consumers during flight, a provision is made for uniting the systems by means of conductor K_c for parallel work of the generators.

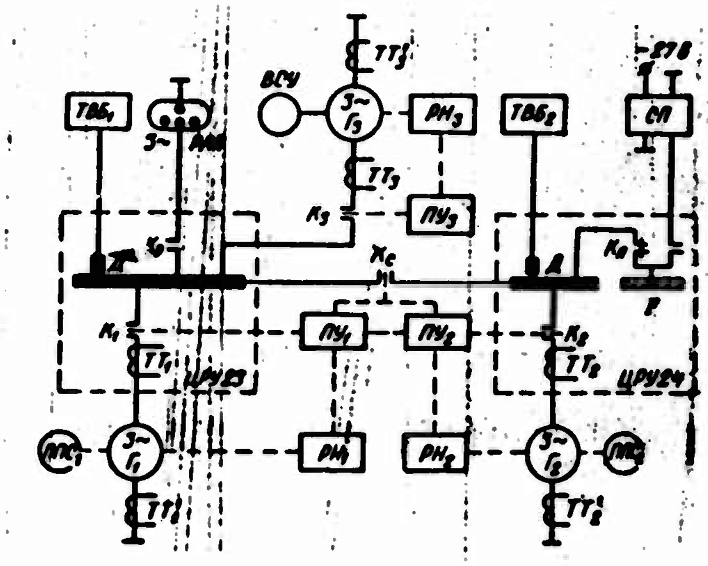

Fig. 6.8. Diagram of an a-c power system with two self-contained systems (unilinear picture): G - generator; K, K_c, K_p, K_Π - are conductors of the generator, synchronization, rose, and transformer; VR - voltage regulator; SP - control and protection panel; TT and TT' - current transformers of the differential protective system; AFR - airfield feed contact rose; SC - static convertor; APU - auxiliary power unit; CSD - constant speed drive.

For the normal distribution of the load between generators, during parallel work in each of the drives of the generator, there is a magnetic head for tuning up the operating conditions. The corresponding signals for controlling these heads is delivered from the load regulators.

The consumer switch serves the landing operations of the aircraft when the aircraft engines stop, and part of the consumers during take-off are supplied with power from an auxiliary power unit (APU) with and emergency a-c generator. The a-c feed on the ground is carried out through the airfield contact rose.

The power system is planned in such a way, that the going out of commission of one of the elements does not result in going out of commission of both feed channels, which improves appreciably the reliability of the power supply to consumers, and the energy distribution only from the central distributing system busbars increasing appreciably the stability of the voltage at the consumers' terminals.

In principle, the power system may be divided into two self-contained systems with any number of generators, assuring in this case their parallel work inside the system and between the systems. In this case the reliability of each self-contained system increases with the increase of the number of the generators.

Section VI. Secondary Power Systems

Chapter I. Secondary A-C Power Systems

1. The Role of the Secondary A-C Power system.

In aircraft along with the main primary d-c power system with a 27 v voltage, secondary power systems with one- or three-phase a-c with constant frequency exist. The power of this system reaches tens of kwA.

Alternating-current of constant frequency is necessary for feeding radio and radar equipment, flying and navigational system, automatic control systems, tracking systems, remote control transmission of orders, amplifying systems, various types of instruments and other consumers.

Moreover, there are consumers which require for their work an alternating-current of any frequency. Among these consumers are the heating elements of the glasses, all light sources, luminescent lighting, etc.

Converters of d-c into single-phase and three-phase a-c with constant frequency are used in these systems as the energy sources. The most widely used are the rotating convertors. However, recently static convertors which have a high reliability have been introduced.

In secondary a-c power systems, the parallel work of convertors was found useless, because of its complexity and insufficient reliability. Systems with automatic switching on of the reserve convertor instead of the principal one which has gone out of commission are becoming widely popular.

The convertor can feed an individual consumer or group of consumers. Owing to a large number of low power consumers, group power supply is being predominantly used. It assures the most rational load on the convertor during the entire flight and makes it possible to lower the power and weight of the principal and reserve converters.

Single-phase convertors should maintain constant: a voltage of 115 v $\pm$ 3% and frequency of 400 cps $\pm$ 5%, the voltage at the consumers' terminals should be 115 v $\pm$ 5%.

Three-phase convertors should maintain constant: a voltage of 36 v ± 3% and frequency of 400 cps ± 2%, while the voltage at the consumers' terminals should be 36 v ± 5%.

To supply power to certain consumers, convertors are installed, which have a high voltage and frequency precision (up to ± 0.05%).

2. D-C to A-C Convertors.

As the energy source in secondary phase a-c power systems, electrical machines and static convertors are converting d-c 27 v into a-c with a constant frequency of 400 cps and a voltage of 115 v (single phase) and 36 v (three-phase) are being widely used.

As the output parameters of the convertor, a substantial influence is exercised by the stability of the input voltage, therefore they should receive feed directly from the distributing busbars of the central distributing system of the primary power system, where during operation the minimum deviations from the voltage from the rated value are provided.

Electric machine transformers MA, PO, and PT consists of a d-c motor with parallel or mixed excitation, a-c generator, synchronous, inductive, or magnetic type, and a control box. For automatic regulation of the output parameters: frequency and voltage, a regulator of the speed of revolution and a voltage regulator are provided.

The motor and the generator are closed in a common body and connected with a single shaft, while the control box is fixed on the body of the machine. The units are made in a protected form with self-cooling.

The electrical properties of convertors are evaluated by a family of operating characteristics (fig. 1.1.) which indicate the dependence of voltage U_2, frequency F, current consumed I, and efficiency η. On the value of load P_2 with the constant feed voltage U = const and constant cos ϕ.

SINGLE PHASE CONVERTORS OF THE MA TYPE are manufactured with capacities of 100 to 1500 vA. In them, inductor generators are used, the principal advantage of which lies in the simplicity of design. However,owing to poor utilization, the active materials in the generators and the non-sinusoidal shape of the output voltage curve ($K_f \approx$ 20%) the use is limited.

SINGLE PHASE CONVERTORS OF THE PO TYPE are built with powers of 100 to 6000 vA. In them, electric motors are used with three types of excitation windings: shunting ShW, series SW, and controlling CW, which is the output of a system of automatic frequency control, and single-phase synchronous generators with outside poles and rotating armature winding.

The principal technical data of the single-phase convertors are given in table 1.1.

THREE-PHASE CONVERTORS are manufactured with capacities of 56 to 3000 vA. In the convertors, electric motors are used with mixed excitation and three-phase electric generators, possessing a high reliability due to the absence of slipping contacts and good form of the output voltage curve ($K_{\phi} < 10\%$). In 1.5 kwA convertors and higher, synchronous generators with electromagnetic excitation are used. The PAG-1F convertor with a capacity of 56 vA is used for individual aid of the consumers. The PT type convertors are made with powers of 70 to 3000 vA and are used for individual and group power supply to consumers.

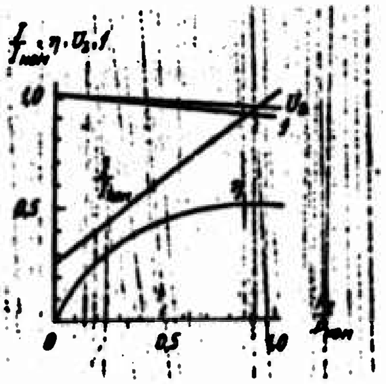

Fig. 1.1. Working characteristics of the consumers.

The principal technical data of three-phase consumers are given in table 1.2.

STATIC CONVERTORS OF DIRECT-CURRENT into alternating current with a frequency of 400 cps are manufactured in two types: the SPO are single-phase with a voltage of 115 v and SPT with three-phase 36 v. In comparison with machine convertors they have a higher reliability, but the considerable weight and distortion of the voltage curve's shape are their substantial short-comings. Therefore, the static convertors as a rule, are made of small capacity and are used as emergency sources of alternating-current.

The simplified diagram of the single-phase static convertor of the SPO type is given in fig. 1.2. The convertor is supplied with direct-voltage current of 27 v ± 10% at the input of the voltage stabilizer, which has a switch-off transistor, which operates upon the rise of the input voltage above the permissible limit, protecting in this way, the convertor from over voltage. Under emergency conditions the convertor permits the drop of the input voltage by 20 v, the latter corresponding to the voltage of an appreciably discharged storage battery.

A stabilized d-c voltage is delivered to the vibrator, which at its output yields a rectangular a-c voltage with a frequency of 400 cps. This voltage is amplified and filtered. At the output of the filter, we obtain a sinusoidal a-c, with a voltage of 115^{+3}_{-8} v, with a frequency of 400 ± 20 cps.

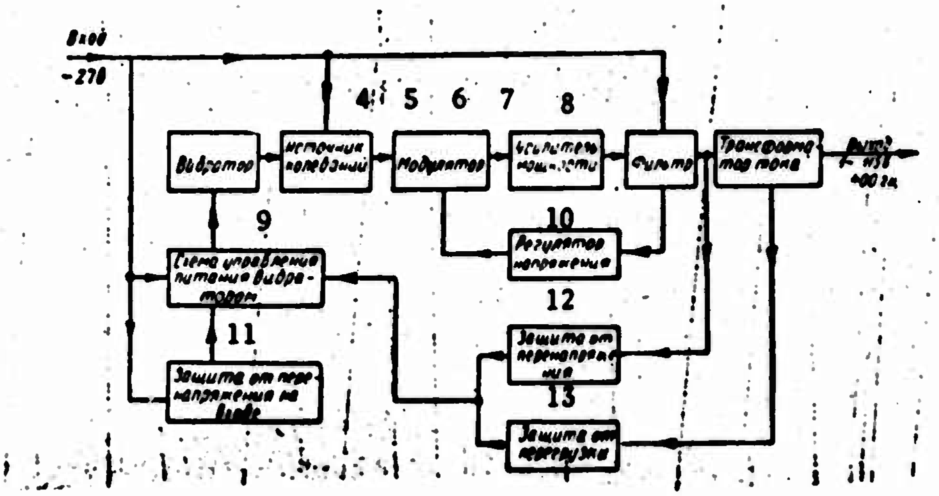

Fig. 1.2. Simplified diagram of a static convertor. Key: 1. input -27v, 2. vibrator, 3. oscillation source, 4. modulator, 5. power amplifier, 6. filter, 7. current transformer, 8. output 115 v, 400 cps, 9. system for controlling feed with vibrator, 10. voltage regulator, 11. protection against over voltage at input, 12. protection against voltage, 13. protection against overload.

The convertor is equipped with a voltage regulator, in which as a voltage standard, a stabilitron is used; the protection against over voltage at the output, and the protective system against overloads.

In the SPT type convertors, with the same voltage parameters of the feed, an output voltage of 36 ± 5 v is assured (in some convertors of rectangular shape instead of sinusoidal) and a frequency of 400 ± 8 cps. In order to increase the reliability in some convertors, two channels are provided: the principal and the reserve channel. Here, the switching over to the reserve channel is performed automatically upon failure of any semi-conductor element of the principal channel.

Table 1.1: Principal Technical Data of D-C to Single-Phase A-C Convertors

1 Тип преобразователя	3 Номинальные данные: 2 Мощность $P_{ном}$, вт	4 Напряжение U, в: 5 двигателя	6 генератора	7 Ток I, а: двигателя	генератора	8 Пусковой ток I, а	9 Скорость, об/мин·10^3	10 Частота, гц	$\cos\varphi$	11 к.п.д.	12 Вес Q, кг	13 $G/P_{ном}$, кг/квт	14 Высота полета H, км	15 Длина, мм	16 Ширина, мм	17 Высота, мм	18 Регулирующая аппаратура: 19 регулятор напряжения	20 коробка переключения	21 выносное сопротивление
ПО-250А	250	27±10%	115±3%	24,5	2,17		12,0	400^{+4}_{-3}%	0,9	0,34	8,0	32,0	8	245	160	215		КРП-1 АПП-1	
ПО-500А	500	27±10%	115±4%	41,0	4,35	300	12,0	400±5%	0,9	0,405	12,5	25,0	16	336	179	250		КРП-1 АПП-1	
ПО-750А	750	27±10%	115±4%	56,0	6,51	415	12,0	400±5%	0,9	0,445	14,8	19,8	16	336	179	259		КРП-1 АПП-1	
ПО-1500	1500	27±10%	115±4%	104,0	13,0	680	8,0	400^{+7}_{-5}%	0,9	0,52	23,5	15,7	15	467	185	291		КРП-1 АПП-1	РС-4
ПО-3000	3000	27±10%	115±4%	190,0	26,1	1240	8,0	400±3%	0,9	0,52	37,1	12,3	15	467	227	328	Р-25В	КРП-1 АПП-1	РС-4
ПО-3000А	3000	27±10%	115±4%	185,0	26,1		8,0	400±4%	0,85	0,51	39,5	13,1	15	457	213	317	Р-27В	КРП-1 АПП-1 КСУ-3000А	РС-4
ПО-4500	4500	27±10%	115±4%	280,0	39,1	1550	8,0	400^{+7}_{-5}%	0,9	0,52	47,0	10,4	15	535	195	337	Р-25В	КРП-1 АПП-1	РС-4
ПО-6000	6000	27±10%	115±4%	370,0	52,1	2040	8,0	400^{+7}_{-5}%	0,9	0,54	58,5	9,8	15	582	252	357	Р-25В	КРП-1 АПП-1	РС-4

Table 1.2.: Principal Technical Data of D-C to Three-Phase A-C Convertors.

1 Тип преобразователя	3 Номинальные данные: 2 Мощность $P_{ном}$, *вт*	4 Напряжение *в*: 5 двигателя	6 генератора	7 Ток I, *а*: двигателя	генератора	8 Пусковой ток I, *а*	9 Скорость n *об/мин*·10^3	10 Частота *гц*	cos φ	11 к.п.д.	12 Вес G *кг*	13 $G/P_{ном}$ *кг/квт*	14 Высота полета H *км*	15 Длина, *мм*	16 Ширина, *мм*	17 Высота, *мм*	18 Регулирующая аппаратура: 19 регулятор напряжения	20 коробка переключения	21 выносное сопротивление
ПАГ-1Ф	56	27±10%	36±10%	3,5	0,65		8,0	400	0,65		3,5	62,5	15	240	114	124			
ПТ-70Ц	70	27±10%	36^{+3}_{-1}%	5,2	1,12		12,0	400^{+2}_{-3}%	0,6	0,3	4,8	68,5	20	230	125	161		КПР-9 АПП-1	
ПТ-125Ц	125	27±10%	$36^{+5}_{-1,5}$%	8,0	2,0		12,0	400±2%	0,6	0,35	5,5	44,0	16	260	150	186		КПР-9 АПП-1	
ПТ-200Ц	200	27±10%	$36^{+4}_{-1,5}$%	14,0	3,2		8,0	400±2%	0,6	0,317	8,5	42,5	18	245	156	196		КПР-9 АПП-1	
ПТ-500Ц	500	27±10%	36±5%	37,0	8,0		12,0	400±2%	0,8	0,4	15,0	30,0		274	222	242		КПР-9 АПП-1	
ПТ-750Ц	750	27±10%	36±2%	49,4	12,0		12,0	400±2%	0,8	0,45	17,5	23,4	20					КПР-9 АПП-1	
ПТ-1000Ц	1000	27±10%	36±5%	60,5	16,1		12,0	400±2%	0,8	0,49	20,0	20,0	18	410	222	243		КПР-9 АПП-1	
ПТ-1500Ц	1500	27±10%	37±1,5%	87,0	24,0	680	8,0	400±2%	0,8	0,51	27,0	18,0	15	410	213	268	Р-27ВТ	КПР-9 АПП-1	
•ПТ-3000Ц	3000	27±10%	208±3%	180,0	8,35		8,0	400±2%	0,85		43,0	14,6	17	516	230	320	Р-27ВТ		

• Продув встречным потоком воздуха 57 *л/сек.*

Table 1.1. and Table 1.2.

1. Type of convertor.
2. Capacity P_{rated} vA.
3. Rated data.
4. Voltage U, volts.
5. Of motor.
6. Of generator.
7. Current I, ampere.
8. Starting current, I, ampere.
9. Speed, rpm x 10^3.
10. Frequency cps.
11. Efficiency.
12. Weight of generator, kg.
13. G/P_{rated}, kg/kwA.
14. Flight ceiling, H, km.
15. Length.
16. Width.
17. Height.
18. Regulating Equipment.
19. Voltage regulator.
20. Switch-over box.
21. Outside resistance.

3. Automatic Regulation of the Output Voltage of the Convertors.

IN CONVERTORS OF THE PO TYPE synchronous generators are used, the output voltage of which is stabilized by automatic voltage regulator, by changing the current excitation winding.

In fig. 1.3 we present a system of voltage regulation of a single-phase synchronous generator of PO type convertor by means of the carbon regulator RC, and magnetic amplifier MA. The alternating resistance of the carbon regulator R_y is connected in series with the generator's excitation winding GEW. The operating coils of generator W_e is connected to the output of the magnetic amplifier (winding W_p) to rectifier B_1.

The current in the operating coils of the regulator depends on the inductive resistance of the magnetic amplifier, which is determined by the sub-magnetizing current, created by the currents running in opposite directions through windings W_{cm} and W_y.

The displacement winding W_{cm}, is supplied through rectifier B_2 from the stabilized voltage, provided by the electromagnetic voltage stabilizer.

The EMS consists of a two-rod core, the rods of which have unequal cross-sections. On the non-saturated rod of a larger cross-section, the primary and compensating coils are wound, on the saturated rod of the smaller cross-section, the secondary coil is wound.

The primary cross-section is connected to the output voltage of the convertor. Upon a variation of this voltage the electromotive force at the terminals of the secondary winding of the stabilizer, be-

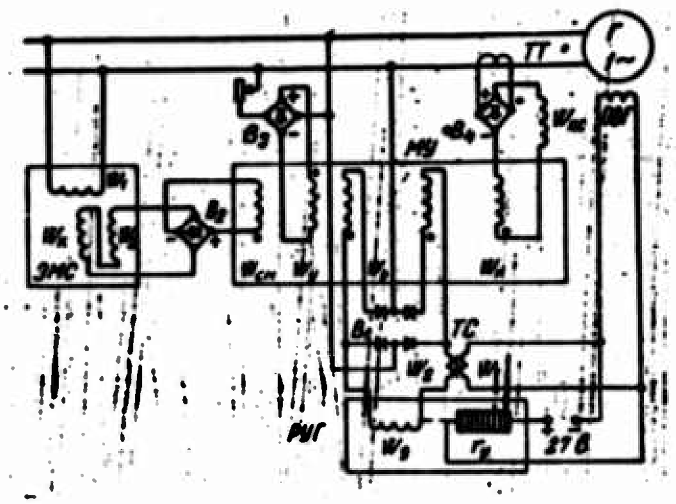

Fig. 1.3. Diagram of regulation of the single-phase synchronous generator of the PO type converter.

cause of the high saturation of the rod, will vary to a considerably lesser degree. In order to compensate, even this small variation of the electromotive force, we connect in series with a secondary winding of the stabilizer and in opposite direction to it, a compensation coil, the electromotive force of which varies proportionally to the voltage delivered.

In this way, at the EMS output we assure a stabilized voltage, equal to the difference between the voltages of the secondary and compensational coils. This is the standard voltage, with which the regulated a-c current is compared. Therefore, W_{cm} creates a constant magnetic flux, which practically retains its value and direction under all operating conditions of the convertor. The introduction of a displacement winding expands the field of utilization of the working characteristics of the magnetic amplifier, and makes it possible to increase the magnetizing force in order to increase its sensitivity.

The control winding W_y is connected through rectifier P_3, directly to the regulated voltage of the generator, and is the sensitive element, reacting to the deviation of the generator's voltage from the prescribed voltage. It creates magnetization of the magnetic amplifier, proportional to the deviation of the generator's voltage. The amplified signal, through rectifier P_1, goes to the coils of the regulator, which change the excitation in the necessary limit, and restores the prescribed voltage level of the generator.

In order to increase the voltage regulation precision during voltage discharges and connection of a load, there is a correcting winding W_k, connected in series with the correcting winding $W_{k.c}$ of the magnetic rate of revolution stabilizer through rectifier B_4, to the secondary winding of the current transformer TT.

In order to disrupt the automatic oscillations, which may originate upon a change in the converter's operating conditions, a stabilizing transformer TS is used.

Upon the change of the operating conditions of the convertor in the secondary winding TS an electromotive force is induced, and a current originates which is always directed in such a way as to smooth out the initial current deviation in the operating coils of the regulator W_e.

The voltage regulators manufactured according to this diagram, provide for stabilization of the output voltage of the convertors with a precision of up to 3%, upon a change of the load from 0 to the rated load and deviation of the feed voltage up to $\pm$ 10%.

IN CONVERTORS OF THE PT TYPE with synchronic magneto-electric generators, the output voltage is stabilized automatically by voltage regulators through a change in the value of the magnetic resistance of the stator's yoke, through a change of the current in the control winding of the generator CG.

In fig. 1.4 we present a system of voltage regulation of the three-phase magneto-electric generator of the PT type convertor. The control winding of the CWG generator is connected to the output of the magnetic amplifier MA through rectifier B_1.

The current in the control winding of the generator is determined by the inductive resistance of the magnetic amplifier, which depends on the resulting magnetization of the current, created by currents flowing through the MA coils: the control winding W_y, successive feed back $W_{o.c1}$, parallel feed-back $W_{o.c2}$ and displacement coils W_{cm}, connected in the opposite direction to them.

The feed-back windings serve for increasing the sensitivity of the magnetic amplifier and are connected in accordance with the control winding W_y. Coils W_{cm} and W_y serve for purposes which were mentioned earlier.

In this way, in the stator's yoke two fluxes are active: the constant, determined by the magnetization force of the control winding of the generator and the alternating, determined by the magnetization force of the magnets.

Upon a change of the current in the control winding of the generator (CWG) the magnetic permeability changes and consequently so does the magnetic resistance of the stator's yoke, which results in a change of the value of the machine's operating flux.

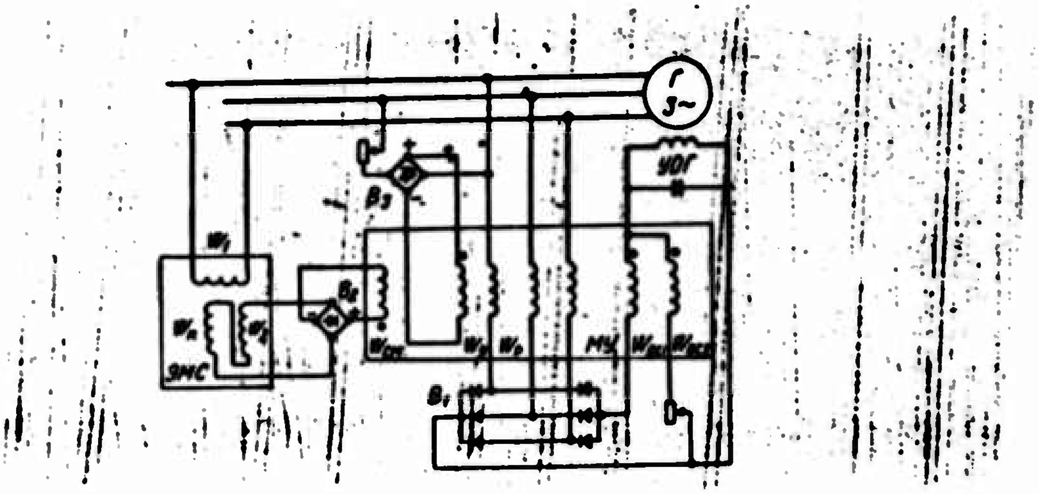

Fig. 1.4. Diagram of voltage regulation of a three-phase magneto-electric generator of the convertor of the PT type.

The voltage regulation process occurs in the following manner. Upon a change of the regulated voltage, the current in the control coils in the amplifier changes, causing a change in the resulting magnetization flux of the amplifier's core and its inductive resistance. As a result, the current in the operating coils of amplifier W_p and consequently the current in the control coils of the generator, changes in such a way, that its voltage at the terminals is reduced to the rated value.

In the convertors of the PT type with synchronic electromagnetic excitation generators, the voltage is regulated according to the system examined for PO. In this case the elements of the regulation system are connected to a phase voltage using the neutral lines of the generator.

In certain voltage regulators, voltage meters VM, made in the form of a bridge with a nonlinear element in one of the parts, are beginning to be used as the sensitive element (see fig. 3.6 of the V. section).

The bridge with the nonlinear resistance has a higher sensitivity and output voltage stability, which makes it possible to raise the voltage regulation precision of the convertor up to ± 1% and higher.

§4. Stabilization of the A-C Convertor's Frequency.

The frequency of the convertor's alternating-current is stabilized by the automatic frequency regulator by assuring the constant rate of rotation of the electric motor by changing the current in its control winding CW.

The frequency regulator consists of three elements: the measuring element in the form of a resonance contour LC; the amplifying element in the form of a carbon regulator or magnetic amplifier; and an executive element in the form of control winding CW of the electric motor.

The frequency is regulated over a closed cycle, i.e., the deviation of the frequency from the rated value is received by the measuring device, the signal from which is amplified and transmitted to the slave element which, acting on the electric motor, restores the frequency practically to the former value.

The frequency regulators are divided into static and astatic, according to the principle of regulation.

In the static regulator, each perturbation value according to load and voltage of the feed, correspond to its own value of frequency with a stabilized regime. Depending on the type of the static regulator, it assures stabilization of the convertor's frequency with an accuracy of up to $\pm$ 0.5%.

The astatic regulator with any perturbation value assures the same value of the frequency in a stabilized regime. Such regulators maintain the precision of frequency stabilization of the order of $\pm$ 0.05%, and higher, and are used in special purpose convertors. As an example of the astatic principle of regulation, we may measure the integral frequency regulator, examined below.

The measuring element for detecting the frequency deviation from the rated value may be the resonance circuit, presented in fig. 1.5.

Usually the circuit is tuned up for the resonance frequency f_{res} = 480-520 cps. In this case with a rated frequency f_{rated} = 400 cps the working point A is located on the left branch of the circuit's characteristics.

In this way, upon deviation of the conductors frequency from the rated frequency, the resulting current of the circuit changes, increases when the frequency decreases and decreases when it rises. This current upon amplification is used for stabilization of the speed of rotation of the electric motor.

THE RESONANCE FREQUENCY REGULATOR WITH A CARBON AMPLIFIER is given in fig. 1.6. The frequency meter is a resonance circuit LC, tuned up for the resonance frequency higher than the rated frequency. Upon the deviation of the frequency from the rated value, the current in the resonance circuit changes, going through the rectifier into the winding of the carbon regulator's electro magnet.

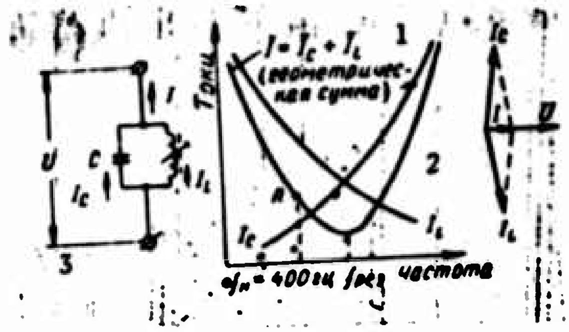

Fig. 1.5. Work of the resonance circuit.
Key: 1. (geometrical sum),
2. 400 cps f_{res} frequency,
3. currents.

The latter, by changing the resistance of the carbon column, changes the current in the control winding (CW) of the electric motor. In this case the excitation current of the electric motor changes in such a way that the frequency would approach the rated value.

The carbon regulator (in the role of the amplifying element) has a limited sphere of application because of its insufficient reliability and decrease of the frequency stabilization precision in the process of operation due to the wear of the carbon disks.

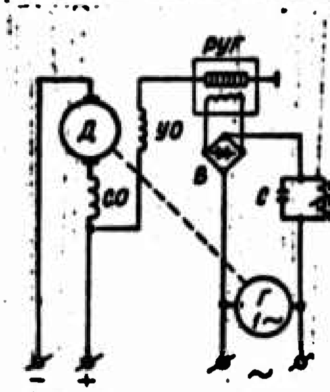

Fig. 1.6. Diagram of the resonance frequency regulator with a carbon amplifier.

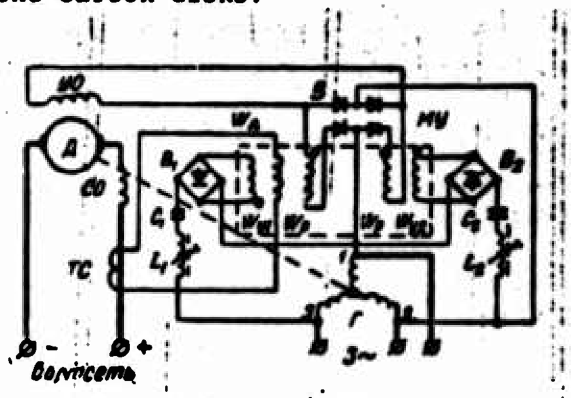

Fig. 1.7. Simplified diagram of the resonance frequency regulator with a differential magnetic amplifier. Key: 1. Aircraft power system.

RESONANCE FREQUENCY REGULATOR WITH A DIFFERENTIAL MAGNETIC AMPLIFIER is presented in fig. 1.7. It assures a frequency stabilization precision of up to ± 1%. The measuring end of the frequency consists of two resonance circuits L_1C_1 and L_2C_2, while the amplifying link is the magnetic amplifier MA, which carries out the role of the variable inductive resistance in the control winding (CW) circuit of the motor.

The operating coils W_p of the magnetic amplifier are connected in such a way, that over each one of them flows a pulsing current, the constant component of which, overmagnetizing the amplifier proportionally to the working current of the load, creates a positive feed back.

The L_2C_2 circuit, tune to a frequency of 450 cps, feeds the control winding (for super-magnetization) W_{y2}, the magnetic flux of which is directed according to the flow of the positive feed-back.

The L_1C_1, tuned to a frequency of 350 cps, supplies the control winding W_{y1} (neutralization) which creates a flux, directed in the opposite direction to the fluxes of the super-magnetization and positive feed-back.

The increase in the voltage of the power supply system or decrease of the load on the generator causes an increase of the rate of rotation of the electric motor, and consequently, the frequency of the alternating current. In this case the current in the super-magnetization's winding increases, and in the neutralization coils it decreases. Owing to the counter-current connection of these windings, the resulting magnetic flux increases, which results in an increase in the core's saturation, and consequently in a decrease of the inductive resistance of the choke coil to alternating-current. In this case, the current in the controlling winding of the electric motor increases, and its speed drops. Upon an increase of the feed voltage or an increase in the load, the regulation process occurs in the opposite order.

With a frequency of 400 cps the currents in the super-magnetization's windings and neutralization windings become equal and their magnetic fluxes are neutralized. To prevent the origination of automatic oscillations, during a change of the convertor's work conditions, stability transformer TS is introduced, the primary winding of which is connected into the electric motor's circuit, and the secondary into the damping coil W_e of the magnetic amplifier.

The change in operating conditions brings out a current pulse, which is transmitted to the damping coils of the magnetic amplifier, and its action is always directed in such a way, that it slows down the change of the current in the control winding of the motor, which originates in it, due to the change in the current of the circuits.

In some frequency regulators with magnetic amplifiers, systems with a single resonance circuits are used. In such systems, there is always a substantial initial super-magnetization of the magnetic amplifier, as a result of which the limits of regulation are lowered substantially.

THE INTEGRAL FREQUENCY REGULATOR with an astatic regulation principle is presented in fig. 1.8.

In the regulators there are two regulation channels: the coarse with two resonance contours PK_1 and PK_2, and fine, with a course prescribing a generator, QPG, and phase discriminator PhD. Both channels are connected in parallel to the differential magnetic amplifier MA, the output from which through rectifier B is delivered to the control winding CW, of the convertor's electric motor.

The coarse channel consists of a resonance frequency regulator, with a differential magnetic amplifier, the operating principles of which were examined earlier.

In the precise regulation channel, the frequency phase discriminator determines the angle of phase shift ψ between the vector of the standard frequency voltage, produced by the QPG, and the vector of the regulated convertor voltage.

The phase discriminator delivers to the magnetic amplifier a voltage, proportional to the cosine of the angle of phase shift $U_{fd} = K \cdot \cos \psi$, i.e., it carries out the integral control with respect to the phase shift angle. Consequently the established operating conditions in the system are possible only with the difference of the standard and regulated frequencies. This signifies, that the convertor is synchronized with the standard frequency source, and the stabilization precision is determined exclusively by the precision of the standard frequency, which for the QPG is about 0.05%.

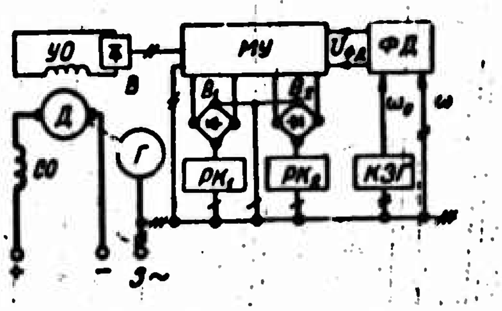

Fig. 1.8. Simplified diagram of an integral frequency regulator with a source of standard frequency.

With a large deviation of the frequency of the transformer from the rated value, the regulation is carried out by the coarse channel, which narrows down the range of the frequency deviation from the rated frequency. In this narrow range the fine regulation channel begins to operate, as a result of which the precision of the convertor's frequency stabilization increases.

§5. Secondary, Single-Phase A-C Power Systems.

In the secondary a-c single-phase power systems the centralized (group) power supply to the consumers is being widely practiced.

Power systems with a separate work of the convertors for a certain specific group of consumers or automatic connection of a reserve source when the principal source fails, have been adopted in practical work.

POWER SYSTEM WITH A ONE-SIDED SWITCHING-OVER OF THE RESERVE CONVERTOR. In fig. 1.9 we present a diagram of a power system with two converters, one of which is reserve, turned on automatically (by means of the switch-box) into the system when the principal one fails.

The Switch-box, SB, disconnected automatically the main convertor and turns on the reserve convertor if the voltage of the alternating current is absent because of:

1. A break in the a-c circuit inside the convertor or in the external circuit before the switch-over conductor;
2. Short-circuit in the generator or feeder line, supplying the a-c consumers busbars (before the switch-over conductor);
3. Short-circuit or break in the a-c feed circuit of the converter.

Introduction of the SB does not exclude the necessity for using the centrifugal switch (CS) of the convertor, but only supplements its protective functions.

In certain emergency cases, for example, when there is a break in the circuit of the control coils of the electric motor, a break in the a-c circuit of the choke coil, etc., only the centrifugal switch operates and then after the convertor is stopped, the SB is turned off.

In other emergency situations: a break or short-circuit in the a-c feed circuit of the convertor, in the a-c generator or feeder line only the SB operates.

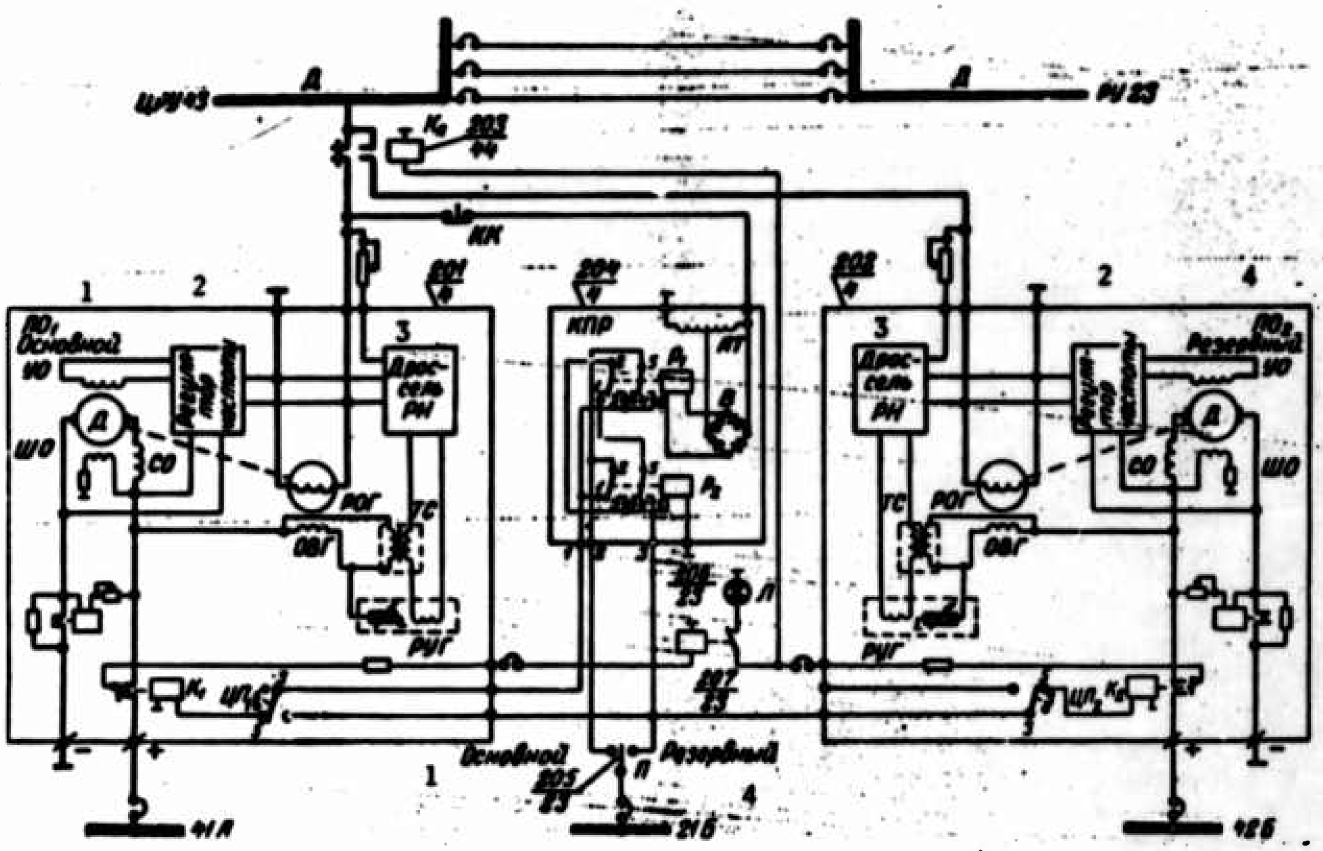

Fig. 1.9. Simplified circuit diagram of the secondary single-phase a-c power system with converter reservation.
Key: 1. main, 2. frequency regulator, 3. choke coil, 4. reserve.

Emergency cases are also possible when the SB and the centrifugal switch of the convertor operate almost simultaneously. This phenomena takes place when there is a break in the operating coils of the generator or the excitation circuit of the generator and a disruption of the brush contact.

Installation of one SB assures a one-sided switch over of the a-c load from the main convertor to the reserve one. One convertor in this case operates the main one, and the other remains in a reserve (it does not turn). For uniform wear of the convertor's during operation it is necessary to switch their positions periodically, in this case, we have in mind their service life with respect to the flight hours, which is practically doubled.

The SB system is collected by two small size switch-over relays P_1 and P_2. Relay P_1 reacts to the a-c voltage value, and relay P_2 to the blocking voltage value. Relay P_1 is connected to the a-c circuit through a step-down automatic transformer AT, and rectifier B, assembled according to the two-half period bridge system.

The one-sided switch-over system operates in the following way. When the switch is set in the "main" position, the aircraft power system voltage is delivered to the static conductor K_1 of the main convertor PO_1 through contacts 2-1 of relay P_2 and contacts 3-5 of the centrifugal switch CS_1. The convertor is started, and through the normally closed terminals K_1 supplies the a-c distributing busbar 43D.

Upon the appearance of a voltage on the a-c busbar, relay P_1 operates, which including contacts 2-3 and 5-6 gives them the impulse to turn on relay P_2 over the following circuit: the + of the power line system aboard the aircraft, - contacts 5-6 and 3-2 - relay P_1 - winding of relay P_2.

Relay P_2 operates and the $\pm$ of the aircraft's power system is additionally delivered to its windings through its own contacts 2-3.

After relays P_1 and P_2 have operated, the system is prepared for fulfilling its tasks in switching over the conductors. Here, the windings of the static conductor K_1 of the principal convertor, are supplied through closed conracts 5-6 of relay p_1 and the feed circuit of the windings of the starting conductor K_2 of the reserve convertor and the switch-over conductor K_{Π} of the a-c feeder is opened only by contacts 1-2 of the same relay P_1.

The absence of an a-c voltage, causes relay P_1 to open its contacts and in this way disconnects the principal convertor and connects the reserve convertor over the falling circuit: aircraft power system +, - contacts 2-3 of relay P_2, contacts 1-2 of relay P_1, contacts 5-6 of relay P_2, contacts 3-5 of the centrifugal switch CS_2, of the reserve convertor.

The signal lamp L indicating the work of the reserve convertor, lights up. In order to protect as big a sector of the a-c feeder as possible, from breaks and short-circuits, the connection point of the conductor, supplying the switch box with alternating-current, should be placed directly next to the distributing busbars.

When the automatic system fails, it is possible to switch on the reserve convertor manually. For this purpose, switch S, should be set in the "reserve" position. In order to check the protective action of the switch box, SB, during operation, a checking-button CB, is provided, which should be normally closed.

For automatic switching over of the convertors, instead of relay switch boxes of the RSB type, we can use switch boxes of the SSB type with semi-conductor elements.

THE POWER SYSTEM WITH TWO-SIDED SWITCH-OVER OF THE CONVERTORS as shown in fig. 1.10, as two RSB switch boxes.

Any of the two convertors installed, may be started and put to work, while the other fulfills the role of the reserve source. The two-sided switch-over system makes it possible to operate more uniformly the convertors installed on the aircraft, turning on alternatively one of the two convertors as the main one.

TWO SELF-CONTAINED POWER SYSTEMS WITH A SINGLE RESERVE CONVERTOR, are shown in fig. 1.11. This system has three convertors and two RSB switch boxes.

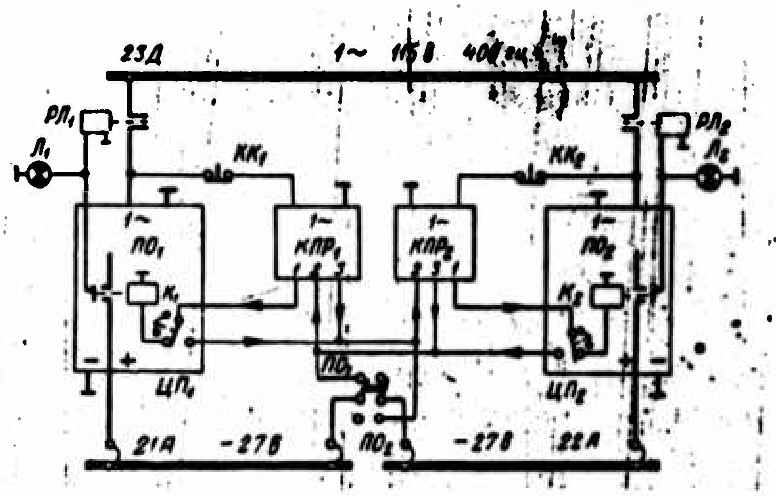

Fig. 1.10. Diagram of a power system with two-sided convertor switching.

Two convertors are the main ones (do not work normally) and the third is called reserve (does not spin). One of the principal convertors works for its own individual a-c busbar. The most important a-c consumers are connected to busbar 23D, and the less important ones to busbar 23E.

The system fulfills the following protective functions:

1. When any one main convertor (PO_1 or PO_2) goes out of commission it is disconnected from the corresponding busbar, and the reserve convertor PO_3 is connected in its place.

2. If first the main convertor PO_1 goes out of commission and then reserve convertor PO_3 will be connected to its busbar; when the main convertor PO_2 will go out of commission, the latter will be disconnected from its busbar 23E and the busbar with the less important consumers will be deprived of current.

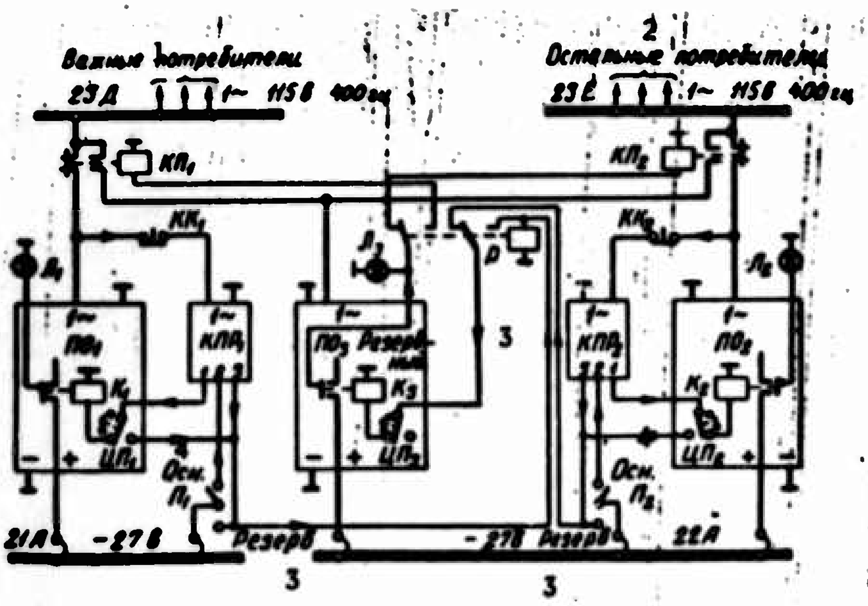

Fig. 1.11. Diagram of two self-contained power systems with a single reverse converter.

Key: 1. important consumers, 2. other consumers, 3. reserve, 4. main.

3. If first the principal consumer PO_2 will go out of commission, the reserve convertor PO_3 will be connected to its busbar, and then the main convertor PO_1 will go out of commission, the latter will be disconnected from its busbar 23D and the reserve convertor will switch over from busbar 23E to 23D, supplying power to the most important consumers.

Apart from automatic connection of the reserve convertor, its manual connection is provided for by setting the switch P_1 and P_2 into the "reserve" position.

The work of each main convertor is signaled to its lit-up bulbs L_1 and L_2. When the reserve convertor is connected to one busbar or another, the bulb L_3 lights up.

6. Secondary A-C Three-Phase Power Systems.

The secondary a-c three-phase power systems usually have a small power on the order of 0.5-3.0 kvA, a voltage of 36 v ± 3% and a frequency of 400 cps ± 2% and supply power to the low power, but important consumers, including the piloting-navigation control systems, and flight control systems.

The parallel work of the convertors did not become practically applicable, because it must meet the same requirement as the parallel work of synchronous generators, and this is connected with complication of the system, increase of the weight, and decrease of reliability.

The parallel work of convertors is rendered more complicated by the fact that they should maintain the prescribed voltage and frequency level at the a-c power system during fluctuations of the d-c system voltage by $\pm$ 10% from the normal, a variation of the load from 0 to rated, and variation of the surrounding mean temperature in a wide range.

Three-phase a-c power systems with a separate work of the convertors for a specific group of consumers and automatic connection of the reserve source, when the main one fails, have practical application.

The structural principles of the secondary three-phase a-c power systems with convertors are analogous to the systems of the secondary single-phase a-c power systems, therefore, as an example, we shall examine only a few of them.

THE POWER SYSTEM WITH A ONE-SIDED SWITCHING-OVER OF THE RESERVE CONVERTOR. The power system, the diagram of which is given in fig. 1.12, includes: 2 three-phase convertors, of which one is the main, the second is the reserve; a RSB switch box; switch S, switch-over contactor K_{Π}; signal lamp L; distributing device DD26 with busbars and a protective system for the consumers.

The SBR switch box is intended for purposes which were noted in §5.

When the switch is set up in the "main" position, the minus is delivered over the following circuit: terminal 5-terminals 5-4 of relay P_4-terminal 8 and winding of conductor K_1 of the principal convertor of the PT_1. The convertor is started and delivers an alternating current to the power system. The a-c voltage goes to the SBR through terminals 1, 2, 3. Relays P_1, P_2, P_3, P_4, operate. Relay P_4 seals itself in. The system is prepared for carrying out the tasks on switching over the convertors.

In the absence of an a-c voltage, relay P_1, opens its contact, which results in the release of relay P_2 and P_3, and relay P_4, is in the operated condition, because it is sealed in. A minus from the switch S, will pass over the following circuit: terminal 5 of SBR-contacts 8-7 of relay P_3-contacts 3-2, of relay P_4-terminal 7 of SBR -terminal 5 and winding K_2 of the reserve convertor PT_2. The reserve convertor is started and connected to the distributing busbar by the switch over conductor K_{Π}, which receives its minus simultaneously with K_2. In this case the signal lamp L "work of reserve converter" lights up.

In order to find out the disruption or the relationships between the voltages in the a-c phases in the SBR there is a filter consisting of R_4; R_3; C_1; R_1; C_2. With the correct phase voltage ratio no current is delivered through rectifier B_1 into winding 1-2 of the magnetic amplifier, and upon disruption of this ratio it is delivered.

Windings 1-2 and 3-4 of the magnetic amplifier are connected in countercurrent, consequently, when the current flows through winding 1-2 the magnetic flux of the overmagnetization decreases and inductive resistance increases, which results in a decrease of the current flowing through the winding of relay P_1. Relay P_1 opens up and the system operates, as it has been noticed above, disconnecting the main convertor and connecting the reserve convertor.

When the automatic switch over system fails, the possibility is provided for turning on the reserve convertor manually by setting up the switch S in the "reserve" position.

For automatic switching of converters instead of relay switch boxes SBR, we can use switch boxes of the SSB type with semi-conductor elements.

TWO SELF-CONTAINED POWER SYSTEMS WITH A SINGLE RESERVE CONVERTOR. In fig. 1.13 we show a diagram containing 3 three phase convertors and 2 RSB switch boxes. The two convertors are the main (normally operating) convertors and the third is in reserve (does not spin). Each of the main convertors operates for its own separate a-c busbar. On the busbar 25D the most important a-c consumers are connected and to busbar 25E the less important consumers are.

The system carries out the following protective functions:

1. When any main converter (PT_1 or PT_2) goes out of commission, it is disconnected from the corresponding busbar, and the reserve convertor PT_3 is connected in its place.

2. If at the beginning the main convertor PT_1, goes out of commission and the reserve convertor PT_3 is connected to its busbars, then the main convertor PT_2 goes out of commission, and then the latter is disconnected from its busbar 25E, and the busbar with the less important consumers will be deprived of current.

3. If first the PT_2 main convertor goes out of commission, and the reserve convertor PT_3 is connected to its busbars, and then the main convertor PT_1 goes out of commission, the latter is disconnected from its busbar 25D, while the reserve convertor is switched over from busbar 25E to 25D, providing power supply to the most important consumers.

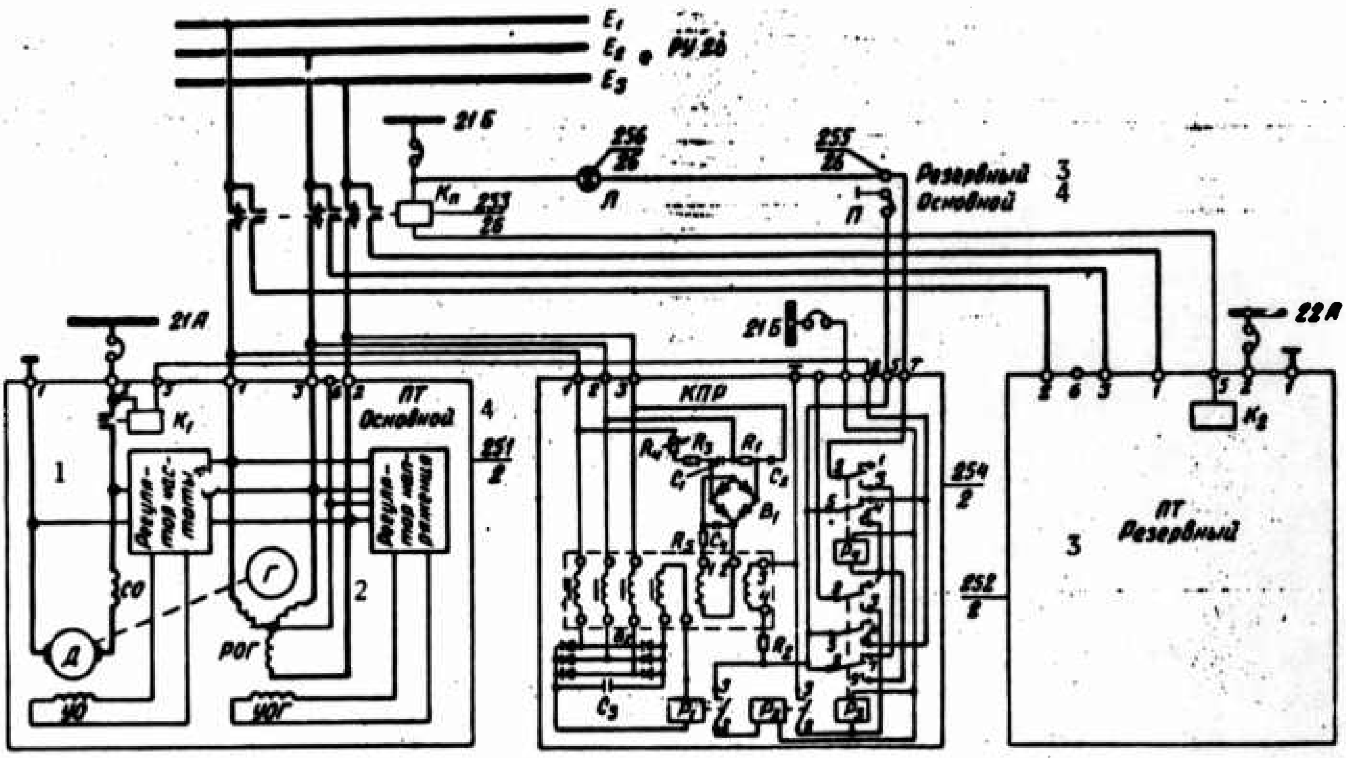

Fig. 1.12. Simplified diagram of the secondary three-phase a-c power system with convertor reservation.
Key: 1. frequency regulator, 2. voltage regulator, 3. reserve, 4. main.

In addition to automatic connection of the reserve convertor, the manual connection of it is provided for by setting the switches S_1 and S_2 in the "reserve" position.

When the reserve convertor is working instead of the main one, lamps L_1 or L_2 light up.

Chapter II. Secondary D-C Electric Power Systems.

§1. Role of the Secondary D-C Electric Power System.

On aircraft with a primary three-phase d-c power system with a voltage of 200/115 v, a secondary d-c power system with a voltage of 27 v is indispensable.

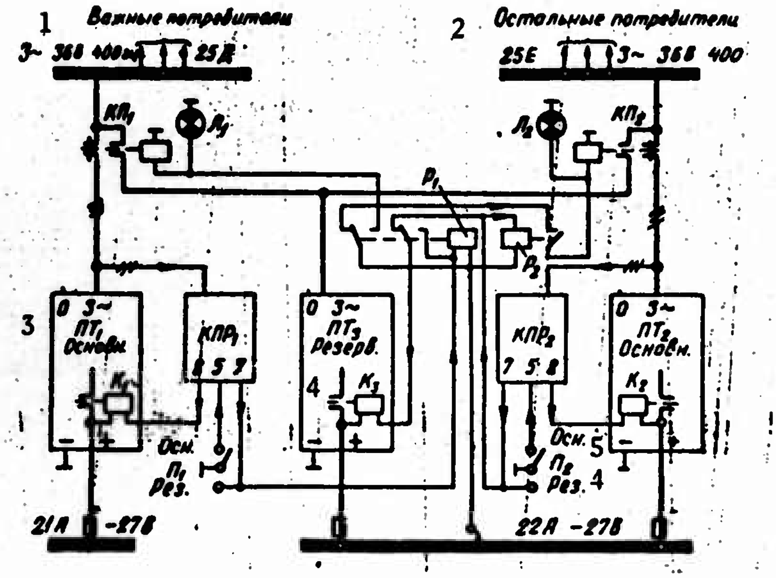

Fig. 1.13. Diagram of two self-contained power systems with a single reserve converter.
Key: 1. important consumers, 2. other consumers, 3. main, 4. reserve.

Direct-current is necessary for feeding: radio communication, radar, navigation-piloting, electro-magnetic relay, electric cranes, control, protection-, and synchronization circuits. The d-c secondary power system is also indispensable for recharging the storage batteries, which are used as an emergency feed source.

The capacity of d-c consumers does not exceed 5-10% of the entire a-c power consumed. However, their quantity is extremely high and they play a substantial role in the reliability in the various systems.

As the energy sources in the secondary d-c power systems'electro-mechanically and statical convertors change, a-c into d-c may be used. Static converters in the form of transformer-rectifier units (TRU) have become widely used in actual practice. In comparison with electromechanical units, they possess a number of substantial advantages: absence of rotating and mobile parts, sparkfree current switching, silent operation, low relative weight (kg/kw), higher efficiency and reliability especially at high altitudes.

In the secondary d-c power systems, three types of connections of TRU are possible: separate for a corresponding group of consumers, parallel for a concentrated load, and parallel for a spread out load.

When a-c generators with a non-stabilized frequency are used as the principal primary sources of energy, we may use rectification devices for creating d-c power systems, used as the principal power supply system of the aircraft.

§2. Circuit Diagrams of Rectifiers Used in Rectification of Alternating-Current.

In fig. 2.1 we present certain diagrams of rectifiers used most widely in rectifying single-phase and three-phase operating currents. In the different variations of the systems, one- or two-half period rectification is provided for.

Half-wave rectification systems (especially single phase) are used seldom, because of the poor utilization of the transformer and large pulsation of the rectified current. The smoothing out of which requires cumbersome filters.

With the conventional full wave system of rectifying single-phase current (system b), the transformer should consist of two secondary windings, connected in series and having a common output.

For three-phase rectifiers, according to the conventional system (diagram h) it is necessary to have a transformer with a six-phase secondary winding, and with an output from the central point. In this case, it is possible to have only one new system of connection of the secondary windings, namely the star-system.

The single-phase bridge system (diagram c) requires only one secondary transformer winding. In this case the total voltage of the secondary winding is equal to one-half of the total voltage of the secondary windings of the conventional full wave system, which results in the decrease of the transformers weight.

Similar properties are possessed by the three-phase bridge system, in which there is a high utilization of the transformer and rectifiers, the absence of forced magnetizing current core, small pulsations of the rectified current, and utilization of the transformer with the conventional connection of the circuit's secondary windings, namely the star or delta system.

In this way, in comparison with the usual circuit diagrams of the rectifiers the bridge systems are distinguished by low inverse voltage, and permit the use of conventional transformers. However, they have a double set of rectifiers of lower power.

The mean value of the rectified voltage U_B, as we know, is expressed by the following formula:

$$U_B = \frac{\sqrt{2}}{\pi} m \sin \frac{\pi}{m} U,$$

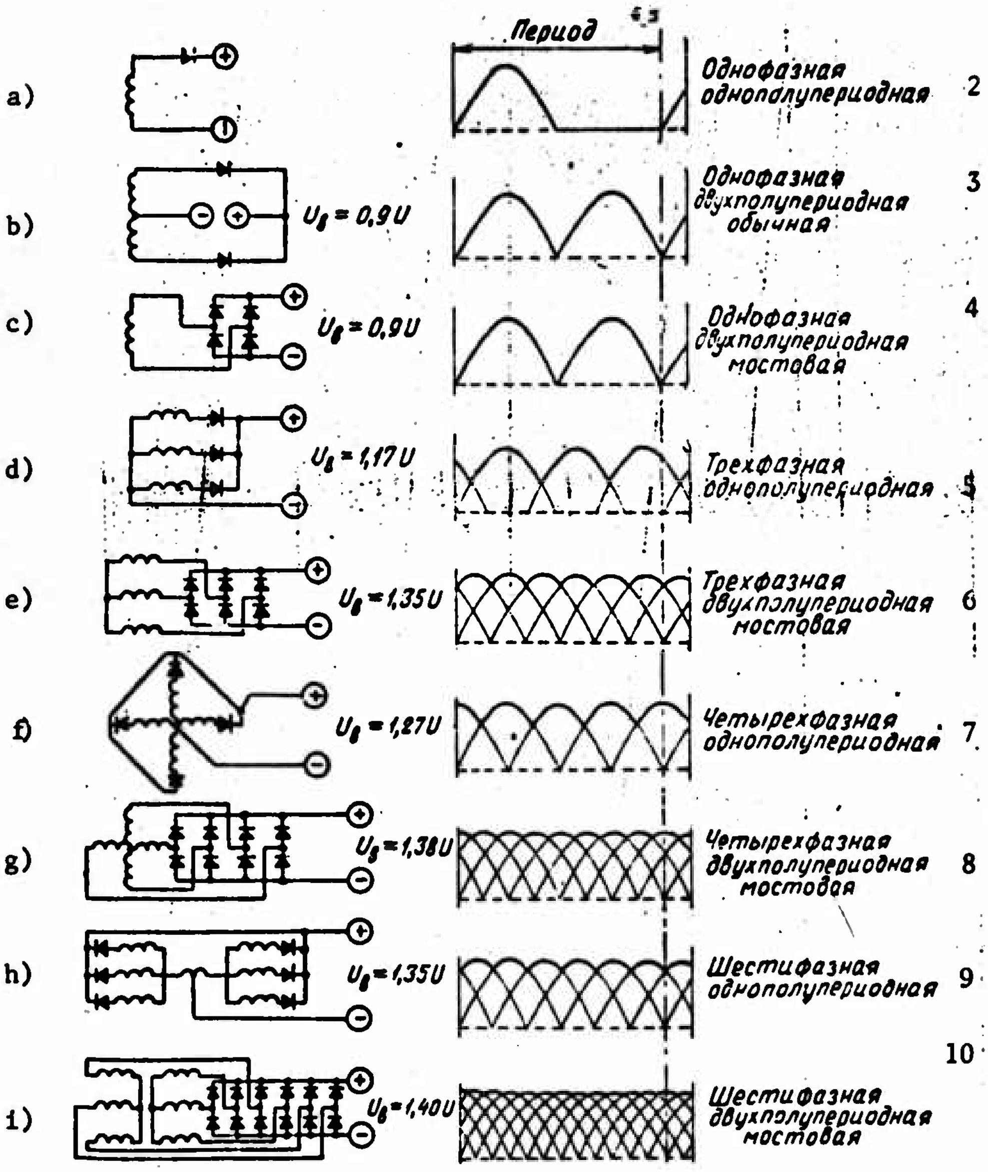

Fig. 2.1. Circuit diagrams of rectifiers used in rectifying alternating-currents.

Key: 1. Period, 2. single-phase half wave, 3. single-phase full wave, conventionally, 4. single-phase full wave, bridge, 5. three-phase half wave, 6. three-phase full wave, bridge, 7. four-phase half wave, 8. four-phase full wave, bridge, 9. six-phase half wave, 10. six-phase full wave, bridge.

where m - is the number of rectified half waves of one;
U - is the effective value of the applied alternating voltage.

Depending on the circuit diagram of the transformers and rectifiers, as it is shown in fig. 2.1, the number of rectified half waves of a single period varies, and proportionally the value of the rectified voltage does so also.

In order to obtain specific rectification systems with certain parameters, semi-conductor rectifiers are collected into rectification columns. In any brdige system the number of rectifiers connected in series and in arm of the system, is found from the equation

$$n = \frac{U_1\sqrt{2}}{U_{rv}},$$

where U_1 - is the effective value of the transformer's voltage, while idling;

U_{rv} - is the permissible reverse voltage per one rectifier.

If for the prescribed load a single element is insufficient, then two or more elements are connected in parallel. The number of parallel branches m is found from the equation

$$m = \frac{I}{i},$$

where I - is the prescribed load current;

i - is the rectified current per one element in the arm for the circuit diagram selected.

Connection of the elements in parallel is permitted if the difference in the values of the voltage drop in the straight direction does not leave the limit of 0.2 v. When the elements are connected in series a difference in the reverse voltages of not more than 2-3 v is permitted.

The efficiency of the rectifier depends on the quality of the rectifier itself, which is determined by the electrification coefficient, on the circuit diagram, the value and the character of the load.

The theoretical efficiency is determined as the ratio between the power of the constant rectified current component to the power of its effective value. In this case it is considered that the resistance of the rectifier in straight direction is equal to 0 and in the reverse direction to infinity. The efficiency of solid state rectifiers under different loads is calculated by the following formula:

$$\eta = \frac{P}{P + \Delta P_{br} + \Delta P_{rv}},$$

where P – is the power of the rectified current;
ΔP_{br} – are the losses in the rectifier in the straight direction;
ΔP_{rv} – are losses in the rectifier in the reverse direction.

The mean value of losses per one period, is

$$\Delta P=\Delta P_{\text{пр}}+\Delta P_{\text{об}}=\frac{1}{T}\left[\int_0^T i_{\text{пр}}U_{\text{пр}}dt+\int_0^T i_{\text{об}}U_{\text{об}}dt\right],$$

where i_{br}; U_{br}; i_{rv}; U_{rv} – are instantaneous values of straight and reverse currents and voltages.

The circuit diagrams of transformers and rectifiers affect the value, shape and frequency of pulsations of the rectified voltage.

The pulsations, acting on the radio-communication equipment, cause noises. An important significance is possessed by the shape of the wave in the pulsation frequency. A frequency of over 20,000 cps having a sinusoidal wave-shape, does not cause sound noises.

The value of the pulsation at any frequency should not exceed 10% of the rated voltage.

For d-c generators, the pulsation frequency is a function of the quality of collector plates and rate of rotation. This frequency, as a role, is above the sonic range.

The principal pulsation of the a-c generator frequency consists of two cycles, three-phase each, i.e., of six pulses per cycle, repeated 400 times per second. The full frequency amounts to 2400 pulses per second.

The pulsations in the rectifiers, especially when the Silicon and Germanium diodes are used, do not form a sinusoidal shape, which consists of a series of harmonics. The frequency of pulsations of these harmonics lies within the range of the sound band.

The pulsation amplitude may be lowered and frequency doubled by means of six-phase transformers, having each two three-phase secondary windings, which may be adapted for half or full wave rectification (diagrams h and i).

If they are intended for a half wave rectification, the secondary three-phase windings, connected in a star, have between them a feed-back through the equalizing reactor. In this case the pulsation frequency will be the same as in the three-phase rectification of a full wave (diagram h).

In the full wave rectifier, in order to rectify a full wave secondary winding of three-phase transformers are connected in such a way as to obtain a shift of linear voltages by 30°, the pulsation frequency being doubled in comparison with the three-phase rectification of full wave (system i).

The storage battery, operating in parallel with the rectifiers, smoothes out the voltage pulsations. When they smooth out the pulsations by condensers, this will result in a certain increase of the weight, therefore it is preferrable to use combinations of transformers and rectifiers which yield a smaller amplitude and a larger pulsation frequency.

3. Diagrams of Transformer-Rectifier Units (TRU).

The transformer-rectifier unit usually contains a transformer, converting the voltage of the primary power system (in this case simultaneously, we may convert a number of phases and produce a zero point) electric rectifiers, in the role of which Silicon diodes are used, and auxiliary devices for regulating voltage, cooling, protection against over heating, and synchronization.

The transformer-rectifier unit is for three-phase a-c, depending on the circuit diagram of transformers and rectifiers, may be divided into four principal types:

1. Three-phase, half wave.
2. Three-phase, full wave.
3. Six-phase, half wave.
4. Six-phase,full wave.

The primary windings of transformers, included in these rectifiers, are connected in a star or delta, depending on the value of feed voltage and the desired grouping of the initial phase of the harmonics, which appear on the side of the rectified voltage, and in the curves of the primary currents. The number of secondary phases of a transformer, is selected as a multiple of the number of the initial phases. With an equal number of phases we obtain a three-phase rectification of a three-phase current, with a double number of secondary phases we obtain a six-phase rectification of a three-phase current. The secondary windings are connected in such a way,that the shift of the voltage vectors of the main harmonics would be 60°. In this case the six-phase system is formed.

The following features serve as a criterion for selection of secondary phases:

1. Tendency to produce minimum pulsations (waviness) in the rectified voltage curve, so as to exclude entirely the necessity of using the smoothing out filter or to simplify it.

2. Tendency to obtain the minimum number and value of harmonics in the a-c circuit in order to prevent the excessive heating of the a-c generators and appearance of resonance phenomena in the a-c power line, which supplies the rectifying units.

3. Assurance of the high level of utilization of the transformer windings, with respect to power, yielded by them to the rectified current circuit.

In three- and six-phase circuit diagrams of the transformers, half wave and full wave rectification is possible.

The full wave rectification doubles the pulsation frequency, since in each phase (through the bridge system rectifier connection) in one period a full wave is rectified, lowering the pulsation amplitude. The increase of pulsation frequency and decrease of amplitude improves the quality of the rectified current, and decreases the size of the smoothing out filters and noises in the radio equipment.

The full wave rectification system provides for a more complete utilization of the windings of the transformers, since by the same output capacity over the windings of the secondary circuit of the transformer flows a current with a smaller amplitude during two half waves instead of one, which results in a decrease of the transformers weight.

With normal work, the transformer-rectifier units are calculated for a change in frequency at the input in the 380-420 cps range. Under emergency conditions, in case of damage to the frequency regulator, the units should permit a frequency change at the input in the range of 360-800 cps. Upon the change of the input voltage within the limits of 200±3 v, and a change in the load from 10% to the rated load, the precision of the output voltage stabilization should be not less than 28 v ±9%. The units should provide for a brief overload (1.5 I_{rated}) during every 15 minutes in work with the rated workload, and an efficiency of 0.8-0.85; cos ψ = 0.95-0.98. The relative weight in relation to the circuit diagram of the transformers and rectifiers fluctuates between 1.4 and 2.5 kg/kw.

In order to remove the largest amount of power, provisions are made for blowing the rectifiers and transformers by means of a fan or with air from the air-conditioning system.

Signals on overheating are provided, working by means of thermal switch, which operates at a temperature of 120-150°C - by the rectifier and of about 200°C by the transformer. The thermal switch is used by sending a warning signal or automatic disconnection of the TRU.

In order to disconnect the TRU upon a change in the input voltage in a small range, there are several stages of switching over the number of coils of the primary winding of the transformer, it being possible to make this switch automatically. At the TRU output a shunt for the ampere-meter is cut.

Let us examine certain specific features of the transformer-rectifier units with specific systems of connections between the transformers and rectifiers, which are used most extensively in the secondary d-c power systems.

THE THREE-PHASE HALF WAVE RECTIFIER Λ/Λ is presented in fig. 2.2. The rectified current has 1200 pulsations per second with a substantial amplitude of the variable component, since in each phase in one period, there is a rectification of only one half wave stop. The quality of the rectified current is relatively low, and for smoothing out pulsations in their decreasing noises, filters are required.

THE THREE-PHASE FULL WAVE RECTIFIER Λ/Λ is presented in fig. 2.3. In the full wave system with a single secondary transformer winding, the rectified current has 2400 pulsations per second, as a result of rectification of the full wave, i.e., the system is equivalent to a six-phase system. Due to the increase of the pulsation frequency, and decrease of their amplitude, the quality of the rectified current is higher as in the analogous half wave system. The smoothing out filters have smaller dimensions, weight, and radio noises.

The system assures a more complete utilization of the iron and windings of the transformers.

THE SIX-PHASE HALF WAVE RECTIFIER $\Lambda/\frac{\Lambda\text{-}12}{\Lambda\text{-}6}$ WITH AN EQUALIZING REACTOR is given in fig. 2.4.

The conventional six-phase system for a half wave rectifier with a 0 output possesses a low utilization level of the iron and windings of the transformer, since the time of the current flow through the winding and the diode amounts to 1/6 of a period stop. Moreover, the current computation relatively deteriorates. The inclusion of an equalizing reactor into the six-phase system with a 0 output increases the time of the current flow through the diode by two times, i.e., the diode and windings operate for 1/3 of a period, twice as much as in the six-phase system without a reactor, which in its turn improves the current computation.

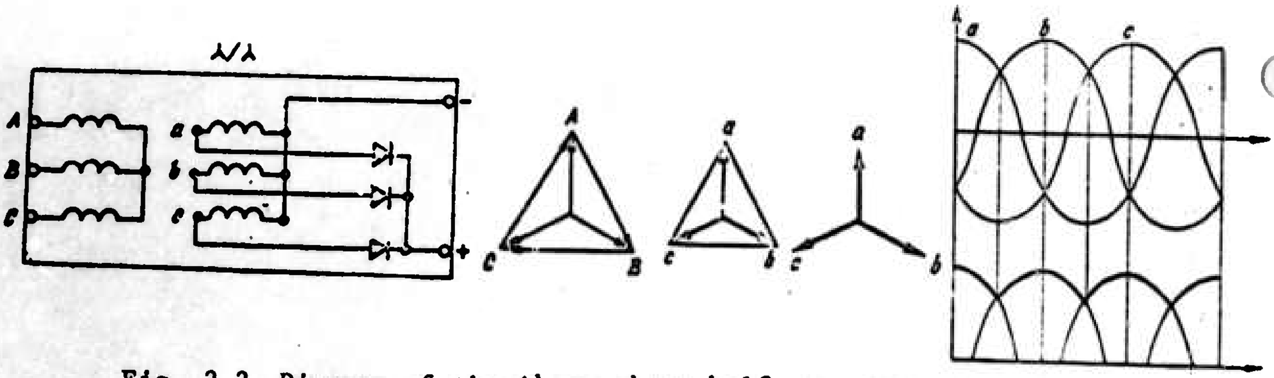

Fig. 2.2. Diagram of the three-phase half wave TRU with Λ /Λ
transformer.

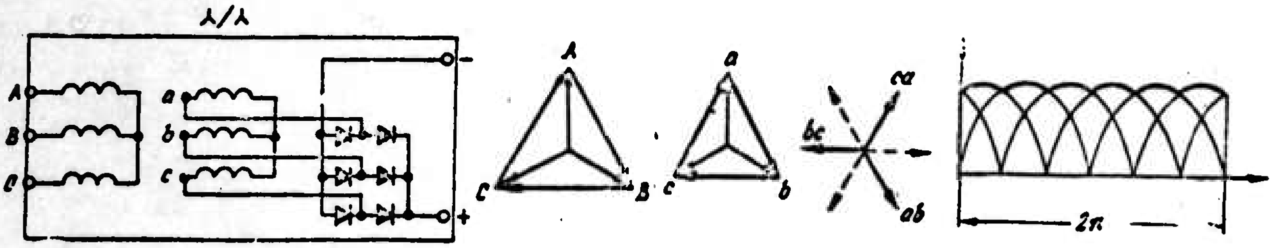

Fig. 2.3. Diagram of a three-phase full wave TRU with a
Λ /Λ transformer.

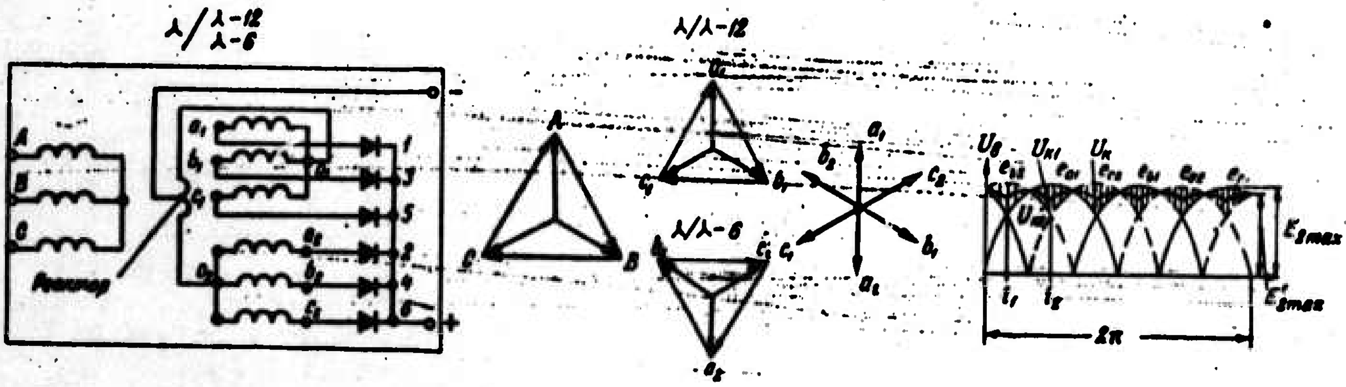

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Fig. 2.4. Diagram of a six-phase half wave TRU with a transformer $\Lambda/{\Lambda\text{-}12 \atop \Lambda\text{-}6}$ and an equalizing reactor. Key: 1. reactor.

The equalizing reactor with a mean output is cut in between the 0 points of stars 0_1 and 0_2, and fulfills the function of a negative pole of the load circuit; the rectifiers serve as the positive pole. The solid lines are used to draw phase voltages of one star and the broken lines the phase voltages of the other star. The difference of the instantaneous values of the phase voltages in the process of their alternation, characterize the alternates of the shaded areas. This voltage difference is active in two sectors of the reactor connected in series. If in one of them only passes a magnetization current, required for this. Due to the fact that the reactor has a closed steel core, the value of the magnetizing current in it is very small; it is sufficient for a current in one of the secondary circuits, passing simultaneously also through the section of the equalizing reactor, to grow by a small value (of the order 1% of the rated value) that the reactor already produces a voltage U_k, which is equal to the ordinates of the shaded areas. Due to the presence in the equalizing reactor of two sectors, in which equivalent voltages are induced,

$$U_{k1} = U_{k2} = \frac{1}{2} U_k,$$

which have different signs with respect to the central output, the anodic voltages within the bounds of a single star decrease by U_{k1} and within the bounds of the other star, increase by U_{k2}. As a result, the anodic voltages in the secondary circuits, which have during this part of the period the highest value of the phase voltages, are equalized, which results in a parallel work of such circuits.

In the time interval $t_1 - t_2$, representing 1/6 of the period, the voltage is equalized in the anodic circuits, which include windings a_1b_2, in connection with the fact that through these windings and rectifiers 1 and 4, currents equal to 1/2 of the rectified currents, each are passing. In the next time interval, equal to 1/6 of the period, the voltages are equalized in anodic circuits, which include windings a_1 and c_2. This process of equalization of voltages and exchange of anodic current, takes place in the other anodic circuits also. In this case the anodic currents in each of the stars change every 1/3 of the period, when the voltage in the next phase becomes higher, than in the preceding one. The anodic currents with respect to both three-phase systems, change every 1/6th of the period stop.

The rectified voltage curve, determined by the bold line passing between the anodic phase voltages, participating in the simultaneous passage of the current, consists of three sections (summits) of sinusoids with six-fold recurrence period stop. The mean of this voltage value is lower than in the six-phase system, operating without an equalizing reactor.

The lengths of the anodic currents during such alternations of their conversions is equal to $2\pi/3$, and the amplitude of the anodic currents is equal to $I/2$. Both of these factors, the increase of length and decrease of anodic current, are favorable, since they bring about a considerable increase of the loading capacity of rectifiers and windings.

THE SIX-PHASE FULL WAVE RECTIFIER $\Lambda/\genfrac{}{}{0pt}{}{\Lambda\text{-}12}{\Lambda\text{-}6}$, as shown in fig. 2.5, has a rectified current with 2400 pulsations per second, i.e., corresponding to the rectified current of the three-phase full period rectifier stop.

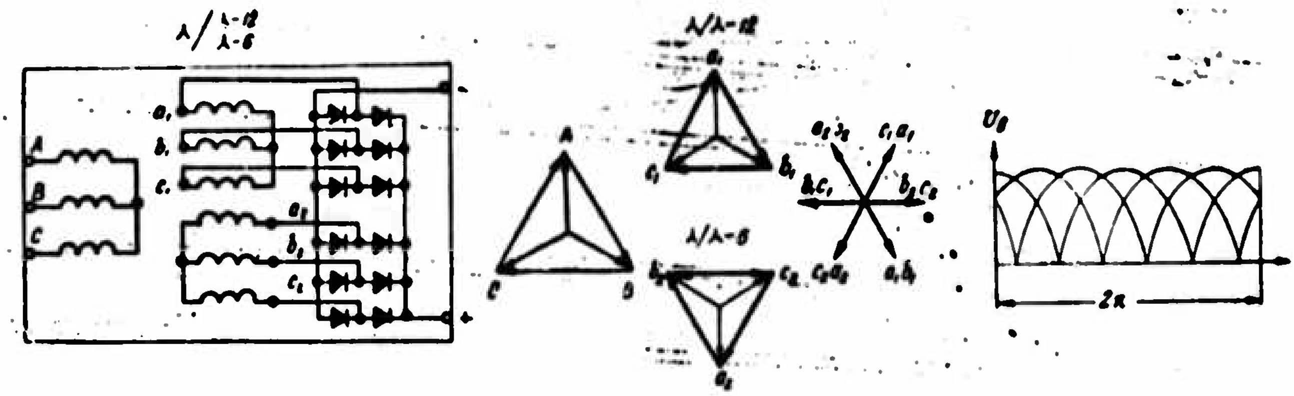

Fig. 2.5. Diagram of the six-phase full period TRU with a $\Lambda/\genfrac{}{}{0pt}{}{\Lambda\text{-}12}{\Lambda\text{-}6}$ transformer.

THE SIX-PHASE FULL WAVE RECTIFIERS $\genfrac{}{}{0pt}{}{\Lambda/\Lambda\text{-}12}{\Delta/\Lambda\text{-}11}$ and $\Lambda/\genfrac{}{}{0pt}{}{\Lambda\text{-}12}{\Delta\text{-}5}$, as shown in fig. 2.6 and 2.7, produce a rectified current with 4800 pulsations per second, i.e., they have a regime equivalent to the 12-phase rectifier. This regime is reached due to rectification of the full wave and a shift of the linear voltages of the secondary transformers by 30°.

Due to the increase of the pulsation frequency or decrease of their amplitude, the quality of the rectified current increases and the dimensions and weight of the smoothing out filters decreases. The system provides for the most complete utilization of the iron and windings of the transformer, as a result of which dimensions and weight decreases.

In fig. 2.7 we show the possible diagrams of switching over of the primary transformer winding coils, cutting in on the ventilators, filters, current control, signalization of rectifier and transformer overheating. The diagrams shown may be used in any transformer-rectifier unit, fully or in part.

From the analysis of the above mentioned TRU system it follows, that the increase of the quality of the rectified current and decrease of the weight, the other conditions being equal, may be reached by means of the most promising systems, presented in fig. 2.4, 2.6, and 2.7.

Let us examine the principal parameters of certain transformer-rectifier units.

THE TRANSFORMER-RECTIFIER UNITS TRU-2.5 (power of 2.5 kw) is built according to the $\Lambda/\frac{\Delta\text{-}11}{\Delta\text{-}5}$, diagram. The rated load of the unit is 100 A. The unit consists of a transformer with a primary winding, connected into a star, and two secondary windings, which are connected into a delta and supply the rectification bridge, consisting of 12 Silicon diodes. With respect to direct current, the bridge is connected in parallel. Three stages of automatic switching of the number of coils in the primary winding of the transformer are provided for with the change of the input voltage. The precision of stabilization of the rectified voltage is equal to $\pm$ 6.6%, the efficiency equals 0.8, the weight 4.4 kg, relative point 1.8 kg/kw, cos ψ = 0.95. A fan is used to cool the rectifier.

THE TRANSFORMER-RECTIFIER UNIT TRU-3 (capacity 3 kw) is made according to the diagram in fig. 2.7. The rated load of the unit is 110 A. During the normal work, the unit is calculated for change in the frequency at the input, within the range of 380-420 cps. In emergency cases, upon damage to the frequency regulator, the unit permits a change in the frequency at the input within a range of 360-800 cps. The unit consists of a transformer with a primary winding, connected to a star, and two secondary windings, connected into a star and a delta. The secondary windings supply the rectification bridge, consisting of 12 Silicon diodes. With respect to the direct-current, the bridge is connected in parallel.

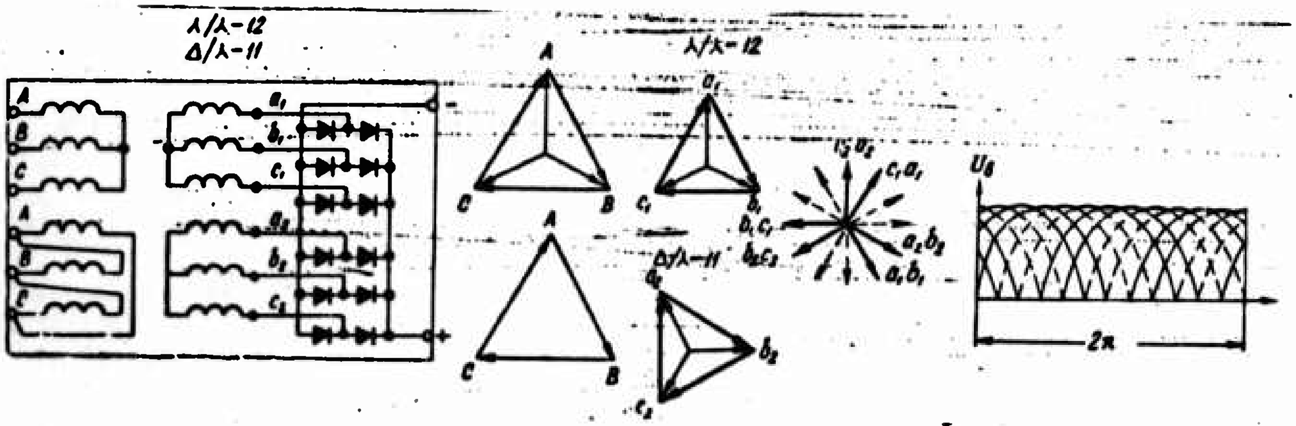

Fig. 2.6. Diagram of a six-phase full wave TRU with transformer Λ/Λ-12; Δ/Λ-11.

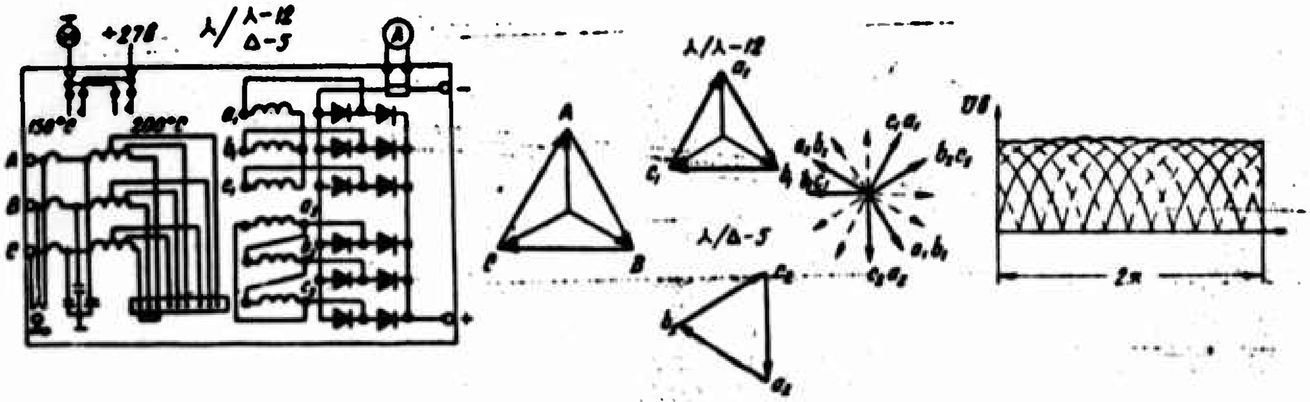

Fig. 2.7. Diagram of a six-phase full wave TRU with transformer Λ/Λ-12 / Δ-5.

The unit provides at the output a voltage of 29 v with a load of 10 A and 25.5 v with a load of 100 A with an input d-c voltage of 204 and 196 v, respectively. With the rated input a-c voltage of 200 v, the unit provides an input voltage of 28.4 v with a current of 10 A and 26.2 v with a current of 100 A. In this way the voltage fluctuation in this case is 2.2 v.

The unit also provides for the protection of the rectifier and transformer against overheating, by means of thermal switches. The thermal switches of the rectifier operate at a temperature of 150°C, and that of the transformer at 200°C. The thermal switches are connected in parallel and close the circuit of the signal lamp. When the temperature of the rectifiers'and transformers' heat drops to 125 and 170°C respectively, the contacts of the thermal switches open and the signal lamp goes out. At the d-c output there is a shunt for an ampere-meter.

The transformer of the unit consists of a single three-phase E-form core and windings made of aluminum. 30-A Silicon diodes are mounted on the cooling ribs, which are insulated from the unit body. When the unit is installed on the aircraft it is assumed that it will be aircooled.

The unit permits a 2 minute overload with a current of 150 A and a voltage of 25.5 v during every 15 minutes of the work under the rated load.

THE TRU-6 TRANSFORMER-RECTIFIER UNIT (power 6 kw) is built according to the diagram in fig. 2.5. The rated load of the unit is 200 A. The unit consists of a transformer with a primary and two secondary windings, connected into a star. The secondary windings supply the rectifier bridge, which consists of 12 Silicon diodes. With respect to direct-current, the bridge is connected in parallel.

The unit contains a thermal switch, operating at 120°C protecting the rectifier and transformer against overheating.

The range of the output voltage is 26.5-32.5 v. The stabilization precision of the output voltage is $\pm$ 10%, efficiency equals 0.8, weight 8.75 kg, relative weight 1.4 kg/kw, cos ψ = 0.98.

4. Separate Work of the Transformer-Rectifier Units (TRU).

The transformer-rectifier unit obtains its power supply from the main a-c power system, its input voltage depends on the precision of the voltage regulator's work of the principal d-c system, and also on the power of the simultaneously connected consumers, which are supplied from the busbars.

With an invariable voltage of the TRU feed, the value of the a-c output voltage depends only on the value of the load.

In fig. 2.8 we show the load characteristics of the TRU with different values of the input voltage. From these characteristics we can see that the change of the input voltage does not affect the permissible value of the current, and each rectifier may be loaded with the rated current, i.e., it can have the maximum utilization factor, equal to 1.

In order to increase the stability of the output d-c voltage, the non-regulated TRU unit should be supplied with power from the primary distributing a-c busbars, when the voltage has a minimum of fluctuations within the limits of tolerance of the main systems voltage regulator.

Let us examine the line with a concentrated load at the end, supplied from the rectifier, which has a constant a-c voltage at the input. In this case the voltage at the input changes only proportionally to the load current.

The voltage oscillations at the consumers' terminals ΔU_{π} should not exceed the permissible value $\Delta U_{\pi per}$ which under normal conditions, is determined by the value of ± 10% of the rated value:

$$\Delta U_{\pi} = U_{\pi max} - U_{\pi min} < \Delta U_{\pi per}.$$

The maximum value at the consumers' end $U_{\pi max}$ is possible only with the maximum input a-c voltage, and the minimum $U_{\pi min}$ only with the minimum input voltage.

The initial sector of the load current characteristics of the rectifier has a very complex variation flow, but this may be avoided by cutting in an insignificant load. In practical calculations the initial sector of the characteristic is excluded by linear decision of the entire characteristic, as it is shown in fig. 2.8. Then the idling voltage of the rectifiers may be conventionally moved with respect to the points with prime signs into points without prime signs, located on line mn. The values of the output idling voltages of the rectifier, obtained in this case, should be used in calculation of the voltage drop in the power line, with a concentrated load at the end of the line.

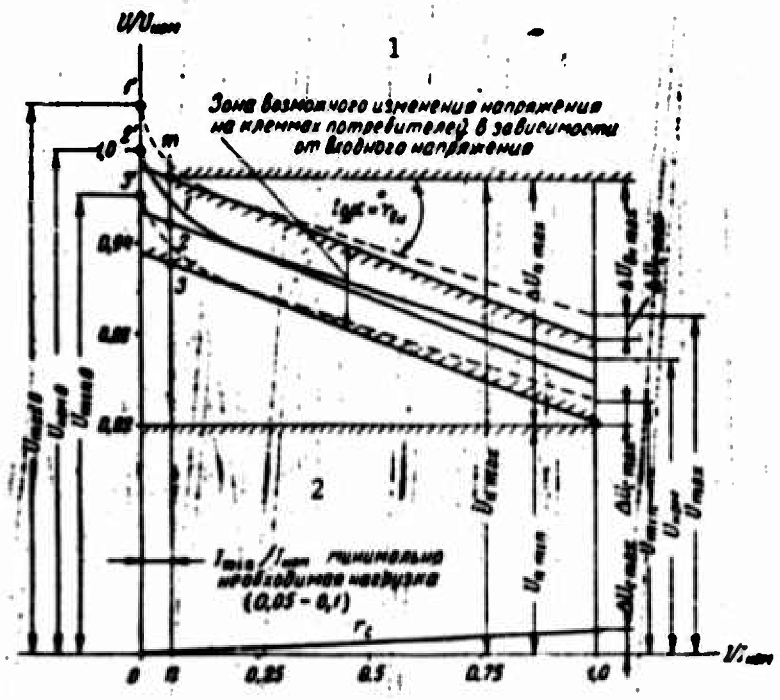

Fig. 2.8. Load characteristic of the TRU with different values of the input voltage.
Key: 1. zone of a possible voltage change at the consumer's terminals in relation to the input voltage; 2. I_{min}/I_{rated}, the minimum required load.

The permissible voltage drop in the power line TRU, to the concentrated load at the end of the line should be calculated, passing from the conditions of the minimum input voltage to the rectifier, caused by the minimum input a-c voltage (point 3).

From the rectifiers' load characteristics, it follows, that the value of the voltage drops ΔU_{bh} and ΔU_c at the resistances of rectifier r_{bh} and powerline r_c, change proportionally to the load and reach their maximum value with its rated magnitude.

In order to obtain greater voltage stability at the consumers terminals, the load will be distributed in such a way, that during cruising flight speed it would have an optimum and constant value.

5. Specific Features of the Parallel Work of the Transformer-Rectifier Units (TRU).

Transformer-rectifier units (TRU) may be made in two variations: with a system of initial voltage regulation, which maintains the voltage at the rectifier's input constant, and without a regulation system, where the output voltage changes depending on the value of the load and power supply voltage.

The use of the regulation system stabilizes the output voltage and assures the most uniform current distribution between the TRU. However, this is connected with the introduction of auxiliary automation elements, complication of the transformers design, which brings about a decrease of the reliability and a considerable increase in the unit's weight.

The units with nonregulated voltage have the simplest design, the lowest weight and dimensions and a high reliability. With rational distribution and optimum feed voltage parameters, the TRU's used can assure normal voltage at the consumers' terminals. TRU's without a regulation system have practical application on aircraft.

The rationality of using TRU's without an input voltage regulation system or with it, depends on the relative weight.

If the relative weight of the TRU with a regulation system is greater than the relative weight of the nonregulated unit, then the latter should be used under the conditions that it assures a satisfactory energy quality.

The relative weight of a TRU without a regulation system depends on a number of units operating in parallel and is determined by the following formula:

[kg/kw],

where G - is the weight of the unit in kg;

n - is the number of units;

I_{per} - is the total permissible current in A;

U_{rated}, I_{rated} - are the rated voltage in v and current of the unit in A;

K_u - is the utilization factor.

The relative weight of a TRU with a regulation system does not depend on the number of parallel operating units, and is equal to:

[kg/kw].

The nature of coincidence of characteristics of TRU operating in parallel affects substantially the uniformity of the load and distribution between them.

Let us examine the work of transformer-rectifier units without an input voltage regulation system.

SPECIFIC FEATURES OF DETERMINATION OF THE QUANTITY AND POWER OF TRU. The method of determination of the quantity and total power of TRU's operating in parallel especially for a spread out load, differs somewhat from the method used in a d-c power system with generators working in parallel.

In a power system with d-c generators, the quantitative distribution of the total load current of the busbars of the distributing devices has practically no effect on the uniformity of their generators' load; it is necessary only that the total load of the consumers will not exceed the total load of the sources taking into account the non-uniformity coefficient.

In a power system with TRU's operating in parallel, in determining the total permissible load of the consumers, it is necessary to take into account only the total power of the TRU's operating in parallel, for the common power system, but also their quantity, places of connection, and distribution of the consumers' loads over the distributing device's busbars. In order to exclude the possibility of overloading the TRU's, it is necessary to plot for each one of them individual load schedules for normal and emergency operating conditions, taking into account the ratio of the load changes on the busbars.

During operation we may encounter different cases of loading of distributing device busbars and rectifying units respectively.

In the process of the checking on the ground and tune-up of the equipment, and daylight flights under uncomplicated meteorological conditions, the load on the rectifiers will not reach their maximum permissible value, but during night-flights in complicated meteorological conditions, the load on the sources increases substantially, however, it should not reach the maximum permissible value.

In order to assure uninterrupted power supply to consumers, the d-c power system should be calculated, taking into account the possibility of individual TRU's going out of commission, i.e., it should have a reserve number of units, operating under a normal regime with an underload.

In planning the d-c power systems with generator, a 75-100% reserve of the number of generators and the corresponding total power is given. In power systems with TRU's the reservation with respect to quantity and power may be decreased to 50-25%, since the rectifiers being static elements, possess a higher reliability than electrical machines.

If the total quantity of TRU's operating in parallel is assumed to be equal to n, then the power available should be estimated with an allowance for the possible going out of commission of any unit, i.e, by n-1. The power of the secondary d-c power systems amounts to not more than 5-10% of the entire electric energy power consumed on aircraft, therefore, in this power system, not more than four TRU's are operating in parallel.

In power systems with generators, the voltage at their terminals is maintained constant with an optimum regulation precision. In accordance with the regulation accuracy, we determine the cross-section of the feed conductors and the voltage drop in them.

In power systems with TRU without voltage regulation the problem of calculation of the feed conductor cross-section and the voltage drop in them is rendered considerably more complicated, because of the non-linearity of the load characteristic, the non-uniformity of the input voltages, non-equality of the load, per each plug, which in its turn increases the imbalance of the source of voltages and loads up the feed power system with additional equalization currents.

6. Parallel Work of TRU for a Concentrated Load.

Parallel work of TRU for a concentrated load is analogous to the work of the primary d-c power system with centralized electric power distribution. However, TRU with non-regulated input voltage have certain specific features. Let us examine the parallel work of two TRU for a concentrated load, the diagram of which is presented in fig. 2.9. The distribution of the current for the two TRU's working in parallel, depending on the input voltage, is shown in fig. 2.10. As we can see from the curves with equal voltage, the TRU are loaded uniformly and their total maximum permissible current is equal to twice the rated current.

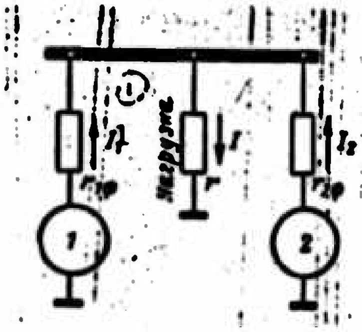

Fig. 2.9. Parallel work of two TRU for a concentrated load.
Key: 1. load.

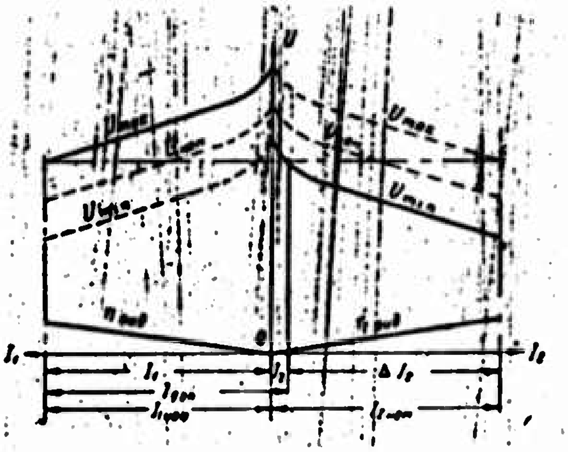

Fig. 2.10. Current distribution between TRU in relation to the input voltage.

With different feed voltage the total permissible load current decreases in proportion to the difference in the input voltages, and should not exceed the maximum permissible value $I_{\Sigma max} < I_{per}$. In this case the TRU having the maximum feed voltage, is loaded with the rated current, and the second TRU takes upon itself the remaining load.

$$I_2 = I_{per} - I_{rated}.$$

With the decrease of the input voltage difference, the uniformity of the TRU load grows and the total permissible load current increases.

The slope of the reduced load characteristic of the TRU is affected by the feeders' resistance. If the feeder resistances are equal, they have no effect on the uniformity of current distribution in parallel work of TRU. If however, the feeder resistances are different, then their effect on the current distributions' uniformity should be taken into account, in aviation practice, the source feeders, as a rule, are made symmetrical and therefore, the slope of their characteristics is equal. Such characteristics are examined in the future.

The effectiveness of the use of TRU operating in parallel is characterized by the utilization factor, which is determined by the ratio between the permissible current load and the total rated current of the TRU operating in parallel:

$$K_u = \frac{I_{per}}{\sum I_{rated}} .$$

For the parallel work of TRU the utilization factor is determined as

$$K_{u2} = \frac{I_{доп}}{2I_{ном}} = \frac{I_{1ном} + I_2}{2I_{ном}} = \frac{2I_{ном} - \Delta I_2}{2I_{ном}} = 1 - \frac{\Delta I_2}{2I_{ном}} .$$

With parallel work of several TRU the total permissible load current changes in relation to the difference between feed voltages. The greater the number of the TRU which have a minimum feed voltage, the smaller is the total permissible load current, which reaches its minimum value in feeding one TRU with a maximum pressure and the other with a minimum.

The total permissible load current, depending on the quantity of TRU operating in parallel is determined as follows:

for two $I_{2per} = I_{1rated} + I_2$;

for three $I_{3per} = I_{1rated} + 2I_2$;

....

for $nI_{n\ per} = I_{1rated} + (n - 1)\ I_2$.

With the increase of the number of TRU operating in parallel and the feed voltage, it is balanced, the utilization effect decreases. To increase K_u we should strive to decrease the feed voltage's imbalance of the units.

7. Parallel Work of TRU for a Spread-Out Load.

The parallel work of TRU for a spread-out load is analogous to the parallel work of d-c generators, connected to spread-out distributing devices. However, TRU with non-regulated input voltage have a certain specific feature in current distribution between the units.

Let us examine the parallel work of two TRU for a spread-out load presented in fig. 2.11. Let us assume that the feed voltage for TRU_1 is higher than that of TRU_2. The maximum permissible loads depend on the character of their connections. Two characteristic cases. of load connections are possible:

1) $I_A \neq 0$; $I_b = 0$;   2) $I_A \neq 0$; $I_b \neq 0$.

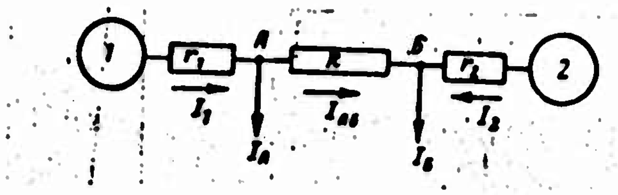

Fig. 2.11 Diagram of the parallel work of TRU for a spread-out load.

1. From the curve (fig. 2.12) it follows that the maximum permissible current of the load connected to point A, depends on the value of resistance R, connected between point A and b. If R = 0, then $I_{d\ A0} = I_{1\ A0} + I_{2\ A0}$, which corresponds to the maximum permissible concentrated load $I_{d\ 0}$ per two TRU connected in parallel. With R>0; $I_{d\ A} = I_{1\ A} + I_{2\ A}$, in this case $I_{d\ A} < I_{d\ 0}$. This decrease of the permissible load of the current is explained by the work of TRU_2 for a load through resistance R. With the increase of resistance R, the permissible current is decreased through decrease of current TRU_2 and with $R = \infty$ $I_{d\ A} = I_{1\ rated}$.

2. If in the presence of resistance R the loads are connected to points A and B, the total permissible load current also decreases with respect to $I_{d\ 0}$, proportionally to the increase of the equalizing current between these points:

$$I_{d\ AB} = I_{1A} + I_{2A} + I_{2B}.$$

With the corresponding load distributions at points A and B, the absence of the equalizing current is possible. In this case each TRU operates for its own load, and the total permissible current reaches its maximum value $I_{d\,0}$.

From the examination of the curve it follows, that if we permit the load at the busbar closest to the TRU_1 equal to its rated current, then the second load will be strictly a specific value, and their total value must not exceed the permissible curve.

The diagram of the parallel work of TRU for a spread-out load represents a line with a two-sided power supply, in which the currents yielded by the rectifying units, are determined by the following expressions:

$$I_1 = \frac{U_1 - U_2}{r_1 + r_2 + R} + \frac{I_A(r_2 + R) + I_B r_2}{r_1 + r_2 + R}$$

$$I_2 = \frac{U_2 - U_1}{r_1 + r_2 + R} + \frac{I_B(r_1 + R) + I_A r_1}{r_1 + r_2 + R},$$

where U_1 and U_2 - are voltages of the TRU with the minimum required load (ca. 0.1 I_{rated});

$r_1 = r_{1f} + r_{1\,in}$ and $r_2 = r_{2f} + r_{2in}$ - are the total resistances of TRU circuit, including its internal resistance r_{in} and the external circuit resistance r_f up to the nearest load.

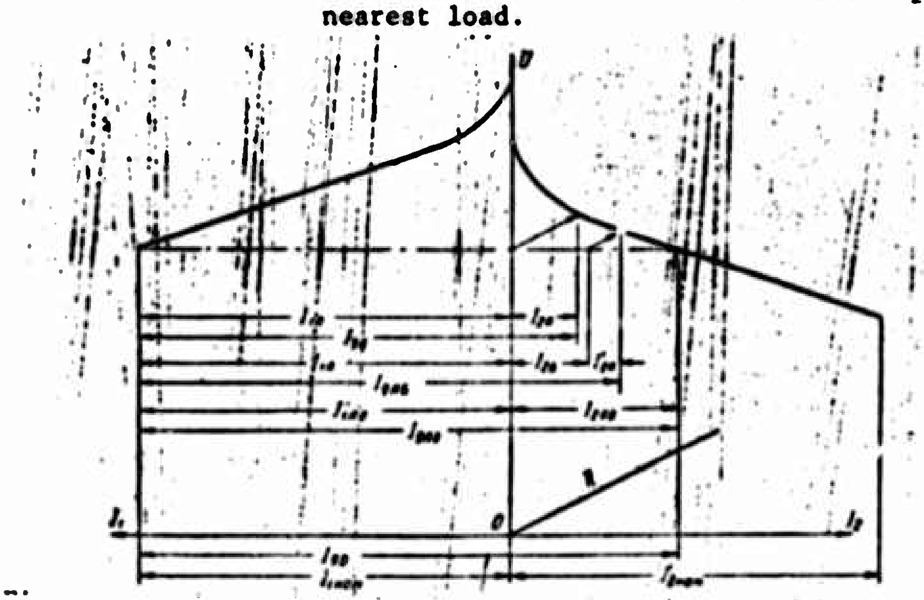

Fig.2.12. Load distribution between TRU operating in parallel.

The first component in the expressions for current I_1 and I_2 represents an equalizing current in the line, caused by the inequality of the rectifier voltages U_1 and U_2.

From the formulas it follows, that even with $U_1 = U_2$ the load rectifiers are loaded non-uniformly and the loads are equalized only with $r_1 = r_2$ and $I_A = I_B$. In this case the current in resistor R is absent.

In this way, as it is the way for the concentrated load, the maximum permissible current of two TRU connected in parallel takes place in the absence of a current through resistance R of the connection between the rectifiers.

With parallel work of several transformer-rectifier units for a spread out load and in the absence of equalization currents, the utilization factor has the same value as in the parallel work of TRU for a concentrated load.

8. Secondary D-C Power System with Separate Work of TRU.

In fig. 2.13 we present a secondary d-c power system with a voltage of 27 v with separate work of transformer-rectifier units (TRU). In the system examined, the energy sources are: three TRU, however, the quantity and power of the rectifiers should be selected in relationship to the requirements for d-c energy and the specific features of the aircraft.

During normal work the power system consists of three self-contained systems with an independent energy source in each. In this case the rated power may be drawn from each rectifying unit.

During normal work, the transformer-rectifier units are calculated for frequency variation at the output, within the limits of 380-420 cps. However, in emergency cases, during damage to the frequency regulator, the units permit a frequency variation at the output with a limit of 360-800 cps, for which the system provides a switch-over of the feed of these units directly into the a-c generator's terminals. During normal work of the power system, each rectifier operates for its own distributing busbars: TRU_1 for busbar 1A, TRU_2 for busbars 2A and 2B, and TRU_3 for busbar 3A.

Unit 2 is the principal one, because it supplies the emergency busbar to 2B, to which the vitally important power consumers are connected. The battery is connected in parallel with unit 2 and directly to emergency busbar. In the circuit of unit 2 a blocking diode is installed, which permits power supply to busbar 2A and emergency 2B from units 1 and 3, but does not permit power supply to busbars 1A and 3A from unit 2.

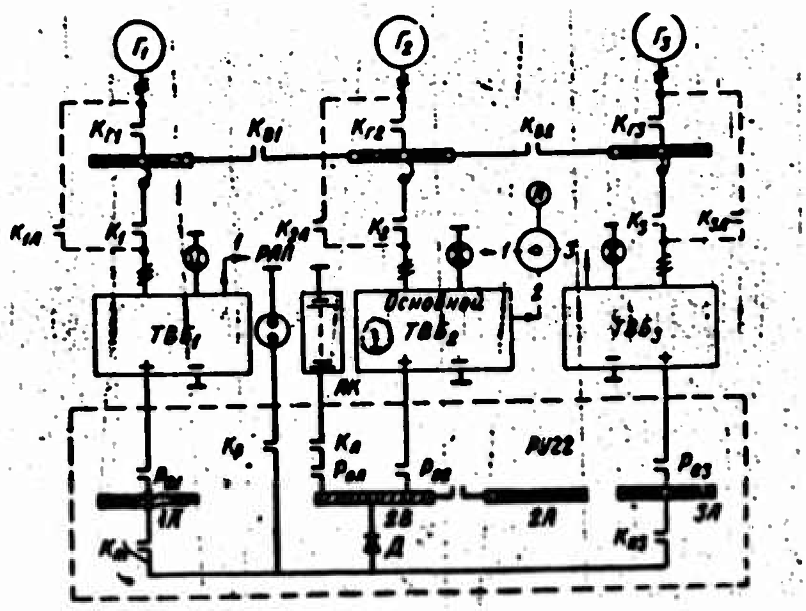

Fig. 2.13. Diagram of a secondary d-c power system with separate work of TRU.
Key: 1. main TRU_2.

The feeder of each TRU, a reverse current relay P_0 is installed, which, in case of short circuit at the output site of the unit, is connected from a power system. The reverse current relay $P_{0.a}$ is provided also in the storage battery feeder line, which upon a short-circuit at the output or inside the battery, disconnects it from the power system.

The system provides for a parallel work of units 1 and 3, which are connected for these operations with conductors $K_{\Pi 1}$ and $K_{\Pi 3}$. In this case their total permissible load during prolonged operating conditions amounts to 1.6 I_{rated}.

When any unit goes out of commission, all the busbars receive power supply from the remaining two units.

The emergency d-c feed is provided upon the failure of all the a-c generators. As the energy source the storage battery is used. The quantity and capacity of the storage battery is in each specific case is determined by the power of the consumers and the conditions of their operation.

Upon failure of all the a-c generators, the storage battery supplies feed for communications, navigational instruments, lighting of the pilot's instrument panel, stand-by lighting and static convertor, which in its turn provides feed for emergency instruments, during the time required for completion of the flight.

Under ground conditions, the battery may be charged from the emergency feed unit of the airfield a-c feed source through a transformer-rectifying unit.

For ground feed of d-c consumers from the airfield source, there is the connection rose with automatic devices, which excludes the possibility of parallel work of airfield energy sources and the aircraft energy sources.

Advantages. 1. The utilization coefficient of the TRU may reach a unit, that is, the rectifier may be loaded for a long time with the rated current power.

2. Uninterrupted feed with high quality energy is provided for one of the duplicating consumers upon damage in the system of the TRU.

Short-Comings. When any TRU goes out of commission (1 or 3) its busbar is temporarily deprived of current, and in this case it is possible to connect it to the remaining rectifier.

In addition to the above stated secondary system, other auxiliary d-c systems are provided with low power full wave rectifiers, which convert alternating single-phase current with 115 v voltage into d-c energy. Such a type of energy, for example, in passenger aircraft, is delivered to the plug-roses of the restroom and the crew's cabins for utility purposes.

The auxiliary systems may be used also in any secondary d-c systems examined below.

9. Secondary D-C Power System with Separate Work and Reservation of Rectifying Units.

The entire d-c 27 v power system is divided into two independent systems, which under normal conditions operate in complete isolation from one another. The diagram of the power system is given in fig. 2.14.

The energy sources in each system are one main transformer-rectifying unit (TRU).

The rectifiers receive their energy supply from the main distributing busbars of the a-c generators and deliver a direct-current to the corresponding main distributing busbars A. Two busbars A, by means of a conductor, a storage battery with its own busbar C, is connected. In this case the rectifier and the battery work in parallel, which reduces the pulsation amplitude of the rectifying current, and removes the peaks of the load, originating when the consumers are connected.

From busbar A, the energy is delivered directly to certain consumers, and the secondary distributing busbars, as well as through the conductor to the auxiliary busbars B, which when necessary may be disconnected, for example, when we convert the feed of the primary d-c power system from the emergency turbine generator.

Each system has its own main switch of the feed sources with 3 positions "on", "off", and "battery isolated". Under normal working conditions, these switches are in the "on" position. When the main reserve TRU fails, the switch is set up in the "battery isolated" position. The battery in this case supplies only the vitally important consumers, connected to busbar C.

When the TRU fails, a signal lamp lights up, the circuit of which is closed by means of the d-c voltage relay, which reacts to the voltage drop of the battery voltage, as 24 v or less.

The reserve transformer-rectifying unit is intended for supplying any system, when the principal TRU fails and there, accordingly is cut in manually, a switch and contactor. Under normal operating conditions, the input and output channels of the unit are turned-off.

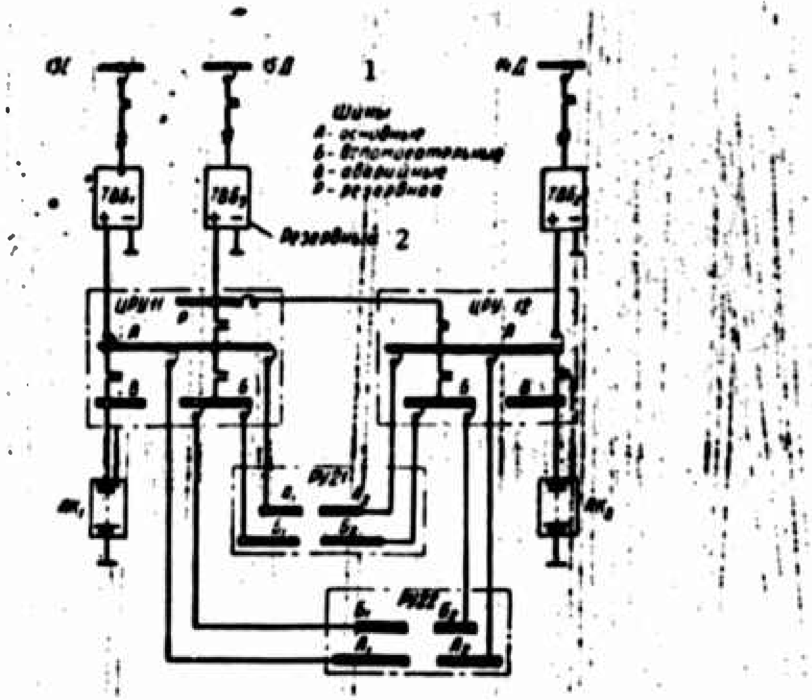

Fig. 2.14. Diagram of a d-c power system with separate work and reservation of the rectifying units.
Key: 1. busbars, A - main, B - auxiliary, C - emergency, D - reserve; 2. reserve.

Under the conditions of the emergency turbine generator work, the a-c feed is delivered only with the reserve TRU. The main TRU in this case are deprived of current, the B-busbars are disconnected, and the batteries supply their own busbars A and C. The reserve TRU may be switched over to parallel work with the batteries of any system.

Under ground conditions the need for direct-current is met through connection of the ground a-c source and setting of the main d-c switches in the "on" position, assuring the turning on of the main TRU.

10. Secondary D-C Power System with Parallel Work of the TRU.

In fig. 2.15 we present a diagram of the secondary d-c power system with a voltage of 27 v and a parallel work of 4 transformer-rectifier units (TRU).

The rectifying unit TRU_1 is the main one, and operates only for its own busbars. Units TRU_2 , TRU_3 and TRU_4 also operate for their own busbars, magnetic cut-in for parallel work to a synchronizing busbar. These rectifiers through a blocking diode D supply feed to the TRU_1, which is especially important if the latter fails.

In the outputcircuits of each unit, reverse current relays are installed, which exclude the passage of energy from open units in good order into the constant field.

Each units is supplied with power in accordance with the generator's a-c busbars. The main unit 1 may receive its feed directly from the terminals of any generator or the airfield source. This switch-over is carried out by special switches.

In the d-c system a storage battery is provided, which may be charged from the main unit 1 or an ampere field source, if its switch is turned on.

When all the TRU fail, the battery supplies power to the main busbar, providing a-c energy to certain principal consumers, required for control functions.

The diagram shows that the main d-c busbar may receive energy from any source: the 4 rectifiers and the battery. From the main busbar, feed is received by the main instrument busbars and the main radio busbar, which may be disconnected manually or automatically from the main busbar, when the rectifying units fail, eliminating the discharge of the battery to the radio consumers.

From the TRU_3 the instrument busbar and radio busbar are receiving their feed, the latter when necessary may have to be turned off.

The work of the a-c power system is controlled by the volt- and ampere-meter, which are connected in series to the busbars of the TRU and the battery.

The simplified diagram of the control is presented in fig. 2.16. The principal merit of this system is the reduction of a number of instruments, while the inclusion of the ampere-meter shunts to the minus circuit, excludes the necessity of using protective devices.

Advantages. 1. It assures the parallel work of the rectifying units.

2. It has a smaller number of fuses.

3. The switch-over of power conductors is almost absent.

4. When there is a short-circuit in the rectifiers' feeder line, only the rectifier with the damaged feeder line is disconnected automatically.

5. During a short-circuit on the busbar, only the damaged busbar and those directly connected with it are taken out of commission.

6. It is convenient for servicing and operation in view of the concentrated arrangement of the equipment.

Short-comings. 1. Presence of busbars connected in series, which reduces their reliability.

2. Concentrated arrangement of equipment and distributing busbars increases the possibility of putting the entire power system out of commission.

11. Secondary D-C Power System with Parallel Work of the TRU in an Angular Diagram.

A secondary d-c power system with a voltage of 27 v with parallel work of the TRU and an angular system of power system lines is presented in fig. 2.17.

The energy sources are four transformer-rectifier units.

The distributing d-c systems are located in places of concentration of the consumers, while the rectifier units are in the direct proximity from them, which makes it possible to raise the reliability with the minimum weight of the power supply system.

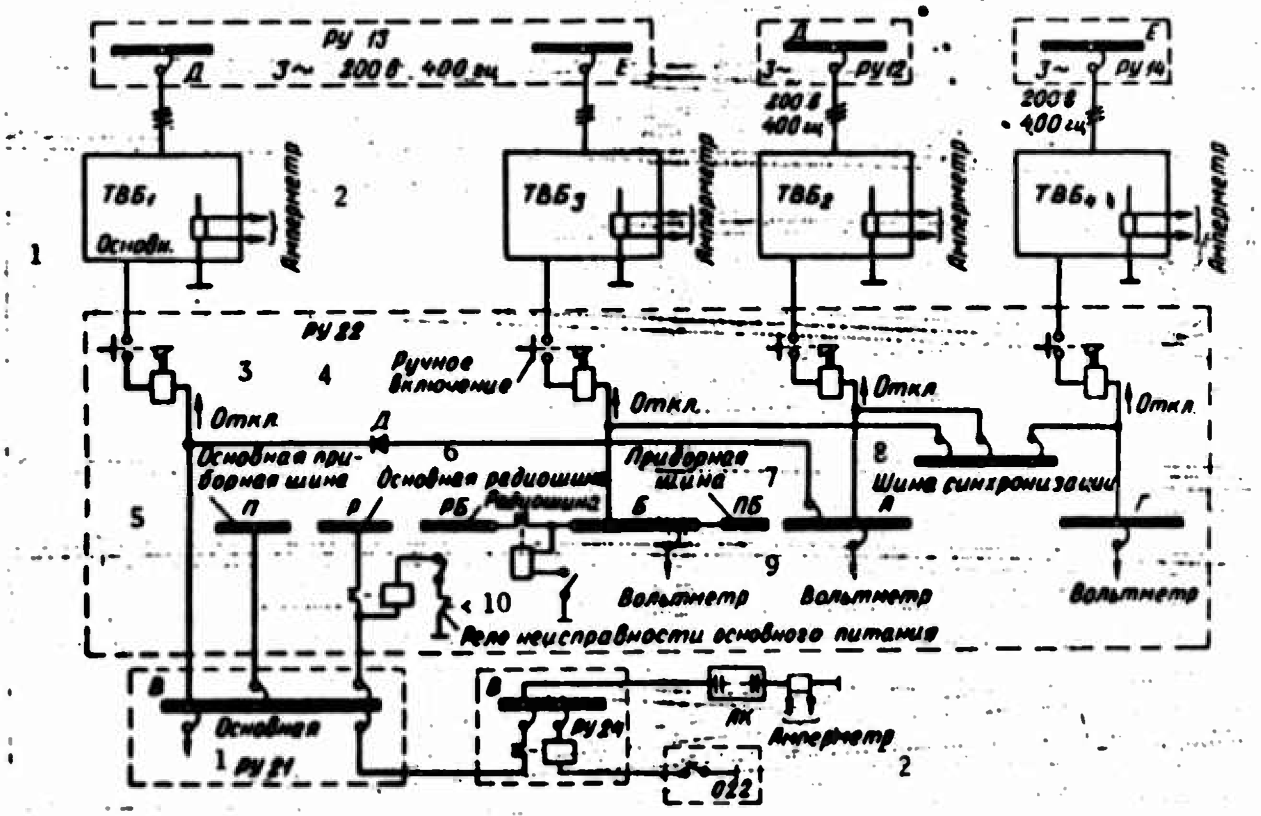

Fig. 2.15. Diagram of the d-c power system with parallel work of the TRU.

Key: 1. main, 2. ampere-meter, 3. off, 4. manual connection, 5. main instrument busbar, 6. main radio busbar, 7. instrument busbar, 8. synchronization busbar, 9. voltmeter, 10. main feed fault relay.

Each TRU is supplied with power from the main busbar and the corresponding a-c generator. In the output circuits of the unit, reverse current relays are installed.

The rectifying units work in parallel for a two-channel electric power ring with a bilateral protection of the power supply lines.

With the normal distribution of the load over the busbars, each rectifier operates for its own central distributing system (CDS) busbar and the connecting conductors between the central distributing system flows an insignificant equalization current, the value of which increases only upon the failure of any one unit. Therefore, the connecting wires have a small cross-section, which however, is sufficient for maintaining a satisfactory voltage on the busbar of the rectifier which has gone out of commission.

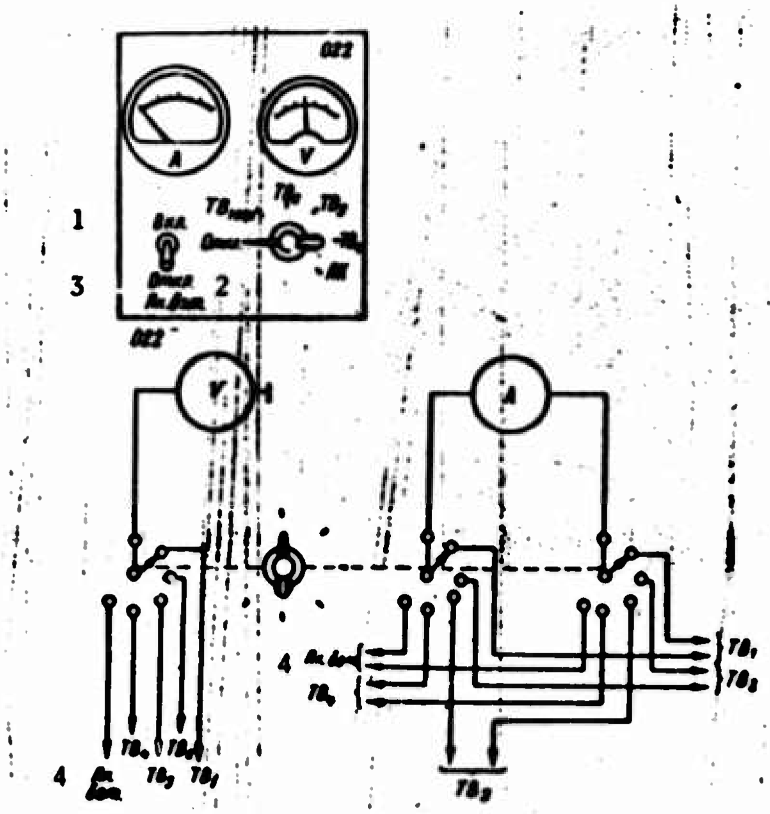

Fig. 2.16. Simplified circuit diagram of the d-c power system control.
Key: 1. on, 2. off, 3. storage battery off, 4. storage battery.

The secondary distributing devices are supplied over a four-channel angular system with a two-sided protection of the conductors.

The angular multi-channel power supply system of the secondary d-c power system, with parallel work of the rectifiers and the two-sided protection of the feeder lines has a higher reliability and vitality, in comparison with the other diagrams of the power supply system.

Advantages. 1. When any source of energy goes out of commission, all the consumers receive a normal power supply through the ring system of the power lines.

2. With a symmetrical distribution of their load over the bus-bars under the normal operating conditions, the equalizing current in the connecting wires is absent.

3. With a short-circuit in any feed line the two-sided protection operates selectively, while the sector of the line with the short-circuit is disconnected from the power system. The consumers receive an energy of practically the same quality.

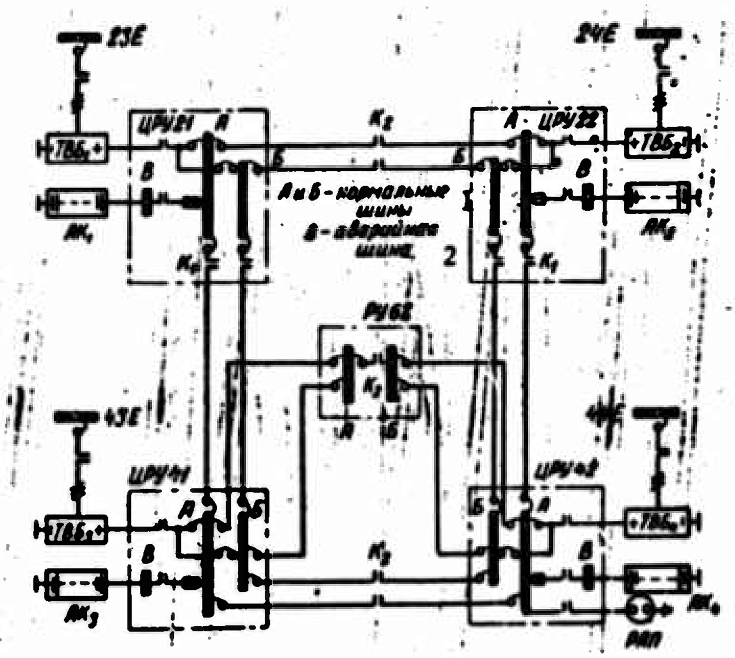

Fig. 2.17. Angular diagram of the d-c power system with parallel work of rectifiers.
Key: 1. A and B - normal busbars, 2. B - emergency busbar.

4. Upon the break of any wire, the power supply to consumers is not disrupted.

5. Upon a short-circuit on any busbar, the protection in the system operates, and the busbar is isolated from the power system. In this case, only the consumers connected to this busbar are deprived of current.

The angular, multi-channel protected power supply system practically retains its vitality up to the last source of energy with multiple short-circuits and breaks of the feed line.

In the power system, four storage batteries are provided, which are connected respectively in parallel with each rectifying unit. Under normal flight conditions, the batteries are charged and remove the load peaks when the consumers with large starting currents are turned on.

When all the TRU go out of commission, the batteries provide the energy to their own distributing busbars, from which especially important consumers required for control and piloting functions receive their power supply.

On the ground, when there is no aircraft source of power supply, the batteries are used for starting the turbine air-conditioning unit and supplying other consumers.

The work of the power system is controlled by means of a volt- and an ampere-meter, connected in series by means of the switch to the energy sources and distributing busbars. The simplified circuit diagram of the control is analogous to the one examined above.

The power rings are provided with conductors K_1 and K_2, dividing the power system into two independent self-contained systems during take-off and landing and during other important flight conditions, for an entirely self-contained feed of the duplicated channels of the consumers.

Section VII. Aircraft Power Supply Systems.

Chapter I. General Information on Power Supply Systems.

1. Connection Diagrams of the Main Distributing Busbars.

In fig. 1.1. we present the typical connection diagrams of four energy sources and main distributing busbars. The choice of the number of energy sources and main distributing busbars, depends on the type and purpose of the aircraft.

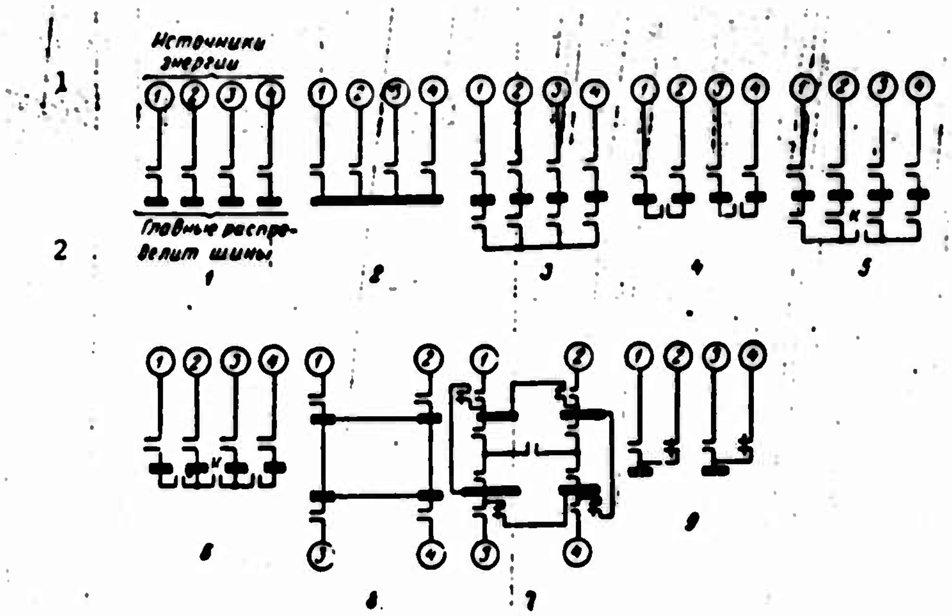

Fig. 1.1. Principal connection diagrams of energy sources and main distributing busbars: 1 - separate; 2 - centralized; 3 - centralized with disconnections; 4 - group; 5, 6, 7 - centralized with switching over to groups; 8 - angular; 9 - with reservations. Key: 1. energy sources, 2. main distributing busbars.

With four energy sources, all the electrical load on an aircraft is divided into four groups in such a way, that the aircraft would be able to continue its flight safety when any of the main busbars would fail. In planning the power systems, we should take all the necessary measures with respect to diagrams, design, and operation, so that the main busbar would not go out of commission. In any case, the failure of one of the busbars (as the result of short-circuit or other damage) should not disrupt the normal work of the others. In case of failure of the main busbar, the consumers directly connected to this busbar lose their power supply. However, the quantity of such consumers may be reduced to a very small number, several times smaller than 0.25 of all the consumers. This is reached by using the angular system for feeding the secondary distributing busbars.

The conductors connecting the generators with the busbars and the busbars with one another may be made with or without protection. Rapid and selective protection improves substantially the reliability and safety of the system during short-circuits.

If a selective protection system is installed, then during a short-circuit at any of the main busbars, only this busbar goes out of commission, if the protection is absent, however, one group or the entire power goes out of order. Diagram #2, is the most vulnerable in both cases.

Upon a short-circuit in the power line, the latter may be disconnected from the power system if it has a selective protection system. In the absence of protection, the system goes out of commission.

When any energy source or its feeder line goes out of commission, not in all the diagrams and not in all the combinations of failures, is the power supply to the main busbars provided. In diagram #1, one busbar is deprived of current. In diagrams 4, 5, 6, and 9, the utilization factor of the sources may be permitted by not more than 0.5. In diagrams 5 and 6, the utilization factor may be increased from 0.5 to 0.67, by turning on the conductor K. In diagrams 2, 3, 7, and 8, the utilization factor amounts to 0.75.

The connection diagrams of the energy sources and main distributing busbars presented, are applicable for both the primary and secondary d-c and a-c power systems. Their merits and short-comings and the rationality of their use under specific conditions are examined in the subsequent sections.

2. Principal Power Supply Systems.

Today, three main power supply systems have become widely used: a-c 27 v, three-phase a-c 200 v, with variable frequency, and three-phase a-c 200 v with constant frequency.

The use of one system of power supply over another is accompanied by the presence of the corresponding primary and secondary power systems. Let us examine their principal features and prospects of application.

The d-c 27 v system is one of the most widely used in the world and is used variably in all types of aircraft. The system is especially convenient for use in aircraft, where the required power does not exceed 9-12 kw per engine. The increase of power and length of power supply system results in a sharp increase of the cross-section and weight of the wires, therefore, the systems are continued to be used in light civil and transport airplanes with a small flight range.

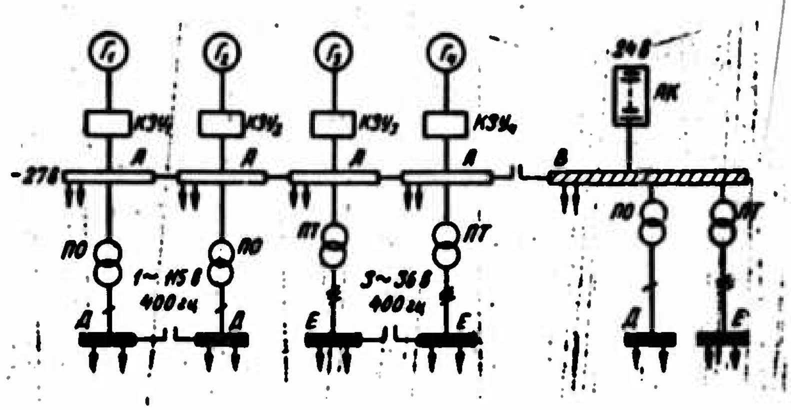

Fig. 1.2. Power supply diagram in a d-c 27 v system.

A typical diagram of the 27 v d-c system is shown in fig. 1.2. It consists of generators with direct drive from the engine. The generators, through their individual control and protective devices (CPD) are connected with the main distributing busbars A, which may be joined between one another with conductors for individual groups or centralized systems. The busbar A may be single, whereas the system becomes centralized. The emergency busbar C under normal conditions is supplied from the main busbar, and under emergency conditions and during idling engines on the ground from the battery. The stabilized-frequency a-c consumers are supplied from the convertors of the secondary sources of the ПО and ПТ type, and under emergency conditions from emergency convertors ПО and ПТ, which receive their power from the battery-busbar.

To supply the consumers which do not require a constant frequency, it is rational to have an auxiliary primary power system with three-phase a-c generators driven by the aircraft engine. On aircraft with turbo-prop engines, the current frequency fluctuates within the limits of ± 5%, which is quite permissible for supplying the majority of the equipment. In this case the capacity of the convertors decreases substantially.

A 112 v D-C SYSTEM is given in fig. 1.3.

For the purpose of safety for its operation and using of the low voltage units, it becomes necessary to create a secondary d-c 27 v system, which receives its power supply from the main system through rotating convertors. The stable-frequency a-c consumers, receive their power supply from convertors of the ПО and ПТ type.

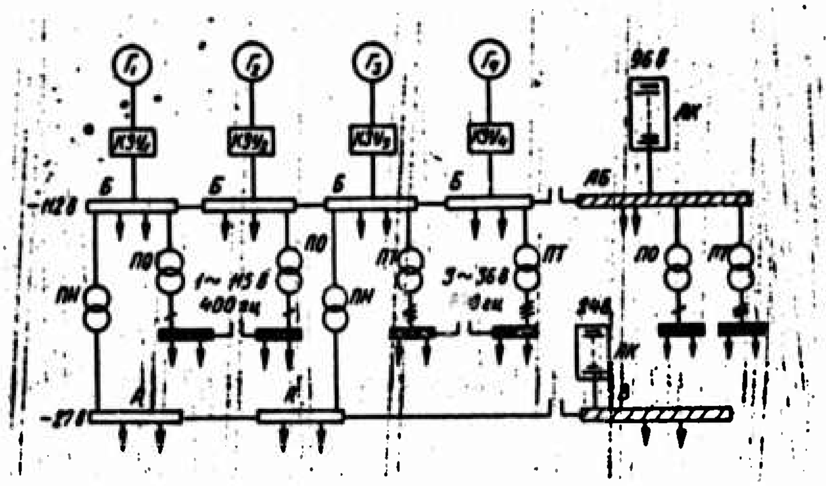

Fig. 1.3. Power supply diagram in a 112 v d-c system.

In case the engines or the generators driven by them go out of commission, the high- and low-voltage system has storage batteries and the corresponding emergency busbars.

The 112 v d-c system, probably will not become widely popular in the future aircraft in connection with the necessity of additional energy conversion and appearance of a 200 a-c volt-system.

THE SYSTEM OF A THREE-PHASE 200 v, A-C CURRENT WITH A VARIABLE FREQUENCY (300-900 cps) is being used in the aircraft where an appreciable part of the power consumed, is used up for heating loads, de-icing devices, utility equipment, lighting and others, which are indifferent to the type of current and frequency.

The typical diagram of the 200 v a-c frequency system is given in fig. 1.4. The a-c generators are driven directly by the aircraft engines. The frequency practically fluctuates in the range between 250-500 cps. The principal part of the power generated is used in the form of alternating-current with an unstable frequency directly from busbars Г.

In order to supply the 27 v d-c consumers, transformer-rectifier units (TRU) are used which convert the a-c into d-c and deliver it to the busbars A.

To supply the a-c constant frequency consumers, convertors ПТ and ПО are used, which deliver the energy to busbars D and E respectively.

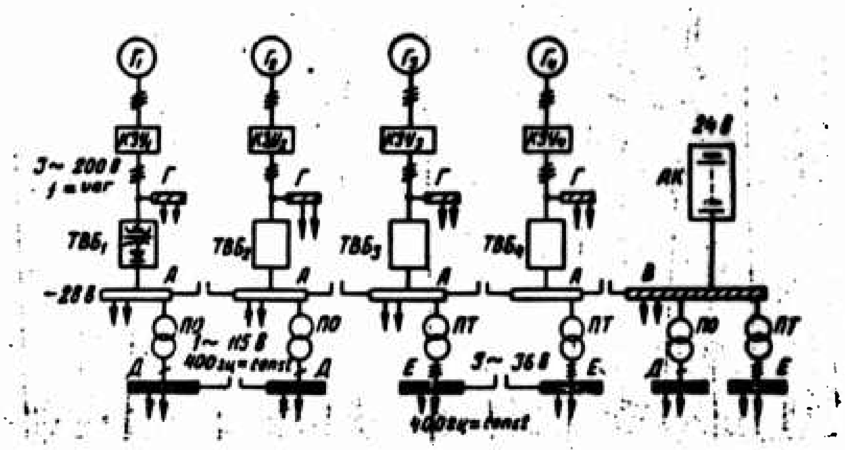

Fig. 1.4. Power supply diagram in the 200 v a-c system with unstable frequency.

Under emergency conditions, the a-c energy source is the storage battery, which supplies directly the low voltage emergency consumers, including the emergency convertors ПО and ПТ.

Since the dimensions and weight of the generator are in inverse proportion to the rate of revolutions, these systems become heavy upon an increase of the aircraft engines' speed range.

The speed or frequency range does not only determine the weight of the a-c generator, but also exercises a serious influence on the dimensions, weight, and operating characteristics of transformers and a-c motors connected with the system. The increase of the velocity range results in a further increase of the weight of the system, however, the simplicity inherent in the system makes it useful in places where the majority of electric energy is used for heating. lighting, and is converted into direct-current.

In as much as it is improbable that in future aircraft with high-pressure turbines, the booster control systems will be used, as well as very high quality automatic pilot- and navigational systems, the unstable frequency system will be first to be selected among the systems for an aircraft of this type.

A SYSTEM WITH THREE-PHASE A-C AND A VOLTAGE OF 200 v AND A STABLE FREQUENCY OF 400 cps ± 5% is quite feasible with turbo-prop aircraft engines. In this case the generators have a mechanical drive, directly from the aircraft engine and may work only individually.

A typical diagram of such an a-c system is presented in fig. 1.5. The principal part of the energy (90-95%) is used in the form of alternating-current, since the frequency with a tolerance of ± 5% is practically satisfactory for almost all the alternating-current consumers.

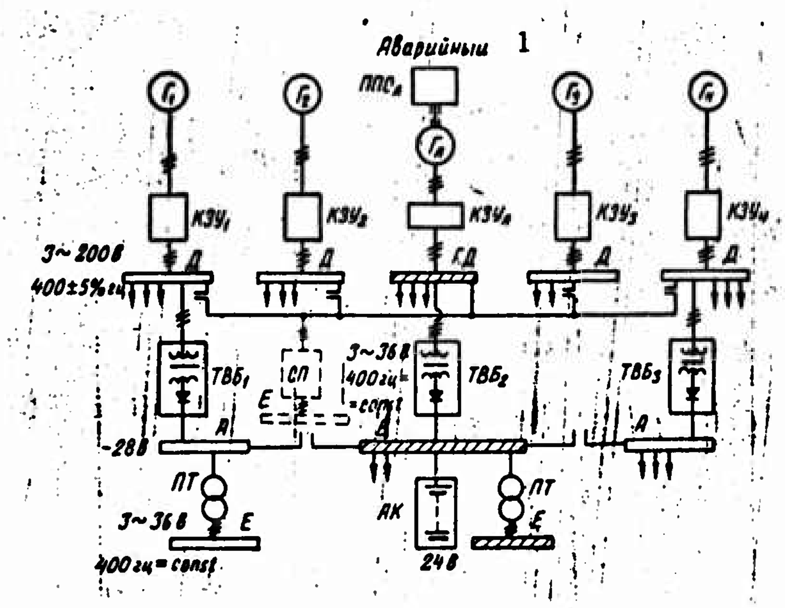

Fig. 1.5. Diagram of power supply in an a-c 200 v system, with a frequency of 400 cps ± 5%.
Key: 1. emergency.

A part of the energy (about 5-10%) is converted into 27 v d-c by means of transformer-rectifier units TRU. The low voltage direct current is used for supplying a large number of low power consumers which in principle require direct current.

A certain part of the d-c energy (3-5%) by means of ПТ convertors is converted into a-c three-phase constant frequency 400 cps ± 2% current with a voltage of 36 v, and is used for supplying piloting-navigational equipment.

However, with the development of static frequency convertors SC, their application in this system will be the most rational, even more so since their capacities are insignificant. In this case it is no longer necessary to have PT convertors and the TRU rectifier capacity will decrease.

The system is simple, highly reliable, has a substantially lower weight in comparison with other power systems, and will be the most promising for turbo-prop aircraft of medium and long ranges.

The three-phase, 200 v, constant frequency, a-c systems, used in modern aircraft are much more perfect than the other systems, and are based mainly on the use of nonconduct elements.

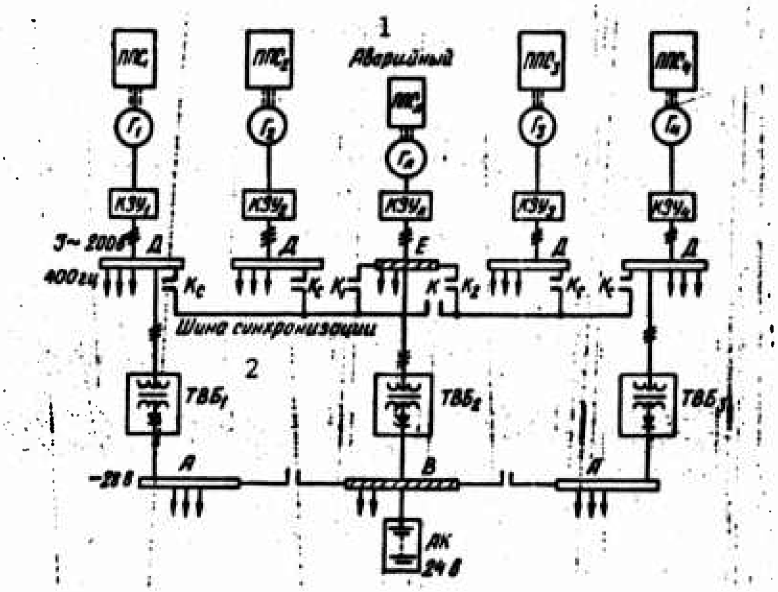

Fig. 1.6. Diagram of the power supply in the 200 v constant frequency a-c system.
Key: 1. emergency, 2. synchronization busbar.

In fig. 1.6, we show the typical diagram of a 200 v constant frequency 400 cps ± (0.1-1)% a-c system. The system includes four constant speed drives, which activate the generators at a constant speed in the entire range of the engine, from the low gas to the take-off conditions.

Each generator is connected to its own main busbar D. The generators are connected for parallel work with conductors K and K_c to the synchronization busbar. Varying conductors K, K_1, K_2, and K_c, can be connected with the generators for separate work or groups of two and other combinations.

In order to assure reliable power supply to the consumers over two channels from two quite independent systems, it is advisable during take-off and landing by means of conductors, to divide the system into two self-contained ones. With the utilization factor of the generators amounting to 0.5, the failure of one of them does not disrupt the number of electric power supply, except that the remaining generator will be loaded 100%. If however, the utilization coefficient of the generators is 0.75, then when one of them goes out of commission, the remaining one is overloaded by 50% of its capacity. In order to avoid this, an automatic system is introduced which closes the conductor and combines two systems, when any one generator goes out of commission. Other combinations are also possible for redistributing the loads.

As an emergency source of stable frequency alternating-current a generator is used which is activated at a constant speed either by an air-fan or auxiliary power unit.

The d-c 27 v voltage is assured by the transformer-rectifier units TRU and low capacity batteries. The latter are used on the ground and for supplying emergency d-c consumers. Under emergency conditions, the TRU, which operates from the emergency generator, supplies power to the emergency a-c busbar.

We should assume that the requirements for the two independent power systems will be expanded and will include aircraft with automatic landing-approach and automatic landing.

The a-c constant frequency systems are suitable for use in all the aircraft where there is a high need for power supply with stable frequency current, therefore, they will be preferrable in the future aircraft with electrical drives in flight control systems and powerful electrical equipment.

These systems will be developed in the direction of the use of contactless generators with oxidation and armature windings located on the stator, and differential and pneumatic drives. Such units may operate at higher temperature than the generators with their rotating rectifiers and hydraulic constant speed drives. The operating temperature of the constant speed hydraulic drives in modern aircraft is limited by the properties of the energy transmitting medium to 160°C. Since in the units rotating parts are used which are manufactured with very small tolerances, their service life is relatively short. They require quite complex hydraulic systems, operating at all positions of the reservoir and negative overloads, and as much as they are installed on the engine, their dismounting for examination and repairs requires a great loss of time and funds. The introduction of the differential or pneumatic drive will solve some of these difficulties.

3. Selection of the Power Supply System.

The total capacity of the electrical systems aboard the aircraft is added up from the sum of the calculated loads, the reserve for the increase of the load during the further development of the aircraft and a reserve for the case of emergency situations.

For civilian aircraft it is common practice to provide for the failure of only one engine and the generator driven by it without a decrease of the load.

The selection of the optimum power system for this type of aircraft depends on the character overloads, their share in the total power, and specific features of operation.

Having determined the power and operating conditions of the consumers, they must be classified with respect to the type of current, voltage, and frequency. At the same time we determine the most economical system for starting the aircraft engine, since in certain cases the start has a substantial influence on the selection of the aircraft's power system. The engine type of the aircraft may be the decisive factor in the selection of the power system. For example, the transport medium range aircraft with a high-pressure turbine may carry a large load in the form of heating elements, de-icing devices for the propeller, engine, and wings. At the same time, the engine has a practically stable speed of revolution with a precision of $\pm$ 5%. In this case absolutely, the most promising is the a-c stable frequency $\pm$ 5% power system with separate work of the generators which are driven directly by the aircraft engines. For low power consumers, requiring high frequency stabilization precision, the energy may be obtained from the convertors, while the d-c 27 v energy comes from the transformer-rectifier units.

In trans-oceanic airplanes with turbo-prop engines, the most rational tangent for the heating elements of the de-icing devices is hot air, drawn from the engine, rather than electricity. At the same time a high-current frequency stabilization precision is required for the communication equipment, control system, navigational system, and other equipment.

Aircraft with turbo-prop engines have a wide range of speed of revolution of the aircraft engine, and consequently two types of power systems are possible: 27 v d-c and 200/115 v a-c with constant frequency and constant speed drive.

For such aircraft with a main 27 v d-c power system a large number of powerful convertors will be used which will increase considerably the weight of an already heavy d-c system in comparison with the a-c system driven at constant speed.

If the load carried by the channels (aircraft engine) is smaller than 9-12 kw, the 27 v d-c system will be the best. These advantages are especially evident when a generator is used as a starter for starting the aircraft engine.

This system is simple and has the batteries as the power reserve. The principal short-coming of the d-c generator is eliminated when a non-conduct design is used. For a light aircraft this system will be the most likely.

When there is a larger demand for circuit power, it is the most probable that the a-c 200/115 v unstable frequency power system will be the most suitable. In this case, direct-current is received from the rectifiers and the a-c constant frequency from the convertors. The decisive significance for the use of the unstable frequency power system is the value of the constant frequency required.

Thus, for every aircraft there exists its own optimum type and power of the power supply system. With the increase of the number of consumers, and the necessity to transmit greater currents at high altitude conditions, it is not rational to use in the aircraft a d-c low voltage as the main power system. The conversion to direct-current of a higher voltage, lowers the quality of the work of the brush-collector units of the generator and for high altitude may prove inacceptable without special protective measures. The numerous radio devices require a wide gradation of the rated voltage used, and conversion of voltages with direct-current is much more complicated than with alternating-current. All this makes it necessary to create the principal electric power supply systems with alternating-current for high altitude airplanes which have a high demand of electrical power. Various convertors, forming the so called secondary feed system, which is not less important than the primary system, are being used simultaneously with the primary power system. The use of convertors of alternating-current into direct-current, cannot have a substantial influence on the weight and other characteristics of the power supply system selected. The use of convertors of direct current into alternating current is connected with the reduction of reliability and increase of the weight of the power system.

4. Tendencies in the Development of Power Systems.

It is considered, that the development of power supply systems of aircra fts will continue in two directions, with the primary alternating-current power supply systems and with primary direct-current power systems. However, the appearance of a qualitative new source of electric energy in them is unavoidable.

The most promising a-c power supply systems are those in which with invariable speed of rotation of the primary motor a constant frequency is obtained without the use of the constant frequency drive, that is, by means of electro-mechanical and static convertors.

In fig. 1.7 we present one of the variations of the simplified circuit diagram, for obtaining a constant frequency of alternating-current by means of a non-conduct electro-mechanical system. At the energy source here, a synchronous asynchronized generator SAG is used, that is, a synchronous generator, built with a multiphase rotor winding, which is supplied from the slipping currents. In these machines, the magnetic field, created by the rotors' winding, moves in the direction of rotation at a sliding speed in such a way that the sum of the mechanical speed of the rotor and the speed of rotation of the electrical field with respect to the rotor is always a constant value, equal to the synchronous speed. On the same shaft with the SAG rotor: the signal generator rotor SG, the rotor of the excitation generator B and the semi-conductor frequency convertor SF. The shafts with all the elements of the system located on it, is put into rotary motion by the engine through the conventional mechanical engine gear with a variable speed.

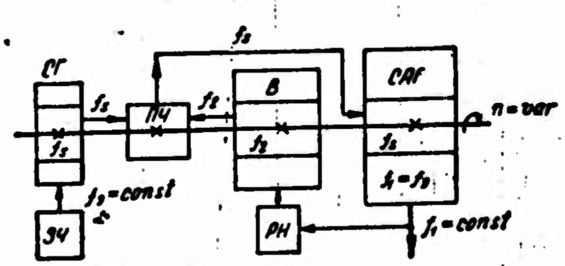

Fig. 1.7. Simplified circuit diagram of an electro-mechanical constant frequency a-c system.

The system includes a low power frequency setter FS generating and alternating-current of a standard frequency f_e, equal to 400 cps. The standard frequency is delivered to the low power signal-generator SG, which, by comparing its own frequency with the standard one, works out the slipping frequency f_s and delivers it to the frequency convertor SF.

The exciter B is the generator of alternating-current with unstable frequency f_2 and serves for exciting the SAG. Its power depends on the range of the speeds of rotation and may reach up to 60% of the power of the main generator.

The frequency convertor SF which has a controlling signal from SG with a slipping frequency f_s, converts the alternating-current of unstable frequency f_2 energy of the exciter into the energy of the alternating-current with a slipping frequency f_s and delivers it to the multiphase rotor winding of SAG. From the SAG stator an alternating current with a constant frequency $f_1 = f_e = 400$ cps, is delivered to the power system. The voltage is regulated by the action on the excitment of exciter B by means of voltage regulator VR.

The merit of the electro-mechanical system examined is the non-conduct structural design, and a relatively low weight per power.

Among its short-comings we should mention the presence on the machine's shaft of a semi-conductor convertor for a relatively large capacity. Up to now the creation of a sufficiently reliable convertor has presented great difficulties.

In fig. 1.8 we present the possible variation of the system of a-c generation with a constant frequency by means of a static convertor.

Generator G receives its variable speed of rotation from the aircraft engine through the usual mechanical reducing gear and delivers to the power system an alternating-current of a high non-stable frequency of 3000 to 6000 cps, which arrives into the SF frequency convertor. On the diagram we show the frequency conversion of only one-phase C. The conversion in the other phases proceeds analogously.

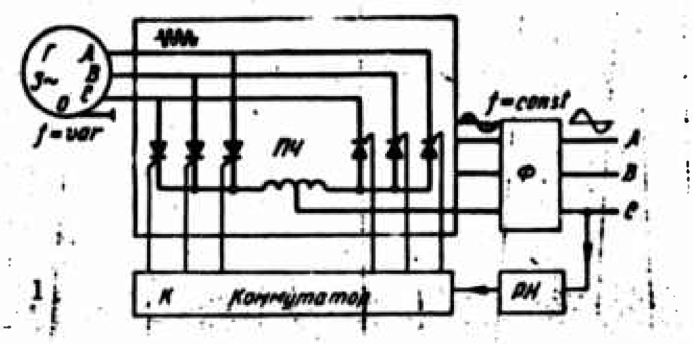

Fig. 1.8. Simplified circuit diagram of the static system of a constant-frequency alternating-current generation. Key: 1. Computator.

In order to obtain a single-phase (for example phase C) with a stable low frequency of 400 cps, 6 regulated diodes were used: 3 for the positive and 3 for the negative half-wave. The computating device K, regulates by opening and closing the diodes, which rectify the positive and negative high frequency half-waves. This regulation is carried out in such a way, that the low voltage frequency (400 cps) would be constant, and in this case for guaranteeing that the low voltage curve would pass through 0, the diodes in this zone should operate in an inverse regime.

In order to decrease the pulsations of the rectified voltage, the systems with six- and twelve-phase rectification are used separately for each phase of the generator.

From the SF, the current goes to filter F. As the result we obtain a constant frequency alternating-current with the shape of the curve close to the sinusoid. The voltage is regulated by the action on the computing device K through the voltage regulator VR.

The merit of the system lies in the fact that it is made non-conduct, and the frequency convertor may be set up by remote control from the aircraft engine, that is, in better temperature and vibration conditions. This improves the reliability, increases the service life, and simplifies the operating conditions.

The improvement of the electrical systems of an aircraft is directed toward the exclusion of throw-over conducts, robbing conduct surfaces, and all moving parts in general.

In all the power systems examined, there is at least one main moving part, namely the rotor. Therefore, the future belongs to the static or direct methods of obtaining electric power, where 3 methods are possible:

1. Direct thermo-electric conversion, using the heat of the aircraft engine's exhaust gas or spatial heat generators.
2. Electro-chemical, using fuel cells, especially if the battery will operate on the aircraft engine's fuel.
3. Nuclear reaction.

The common feature of these methods consist of the fact that they generate direct-current, and the need for a-c electric energy apparently would be met by some type of convertor.

The great obstacle in designing electric aircraft power systems, is the so called 'heat barrier stop" during flight with a speed corresponding to M-2 at a height of 18,300 m, the cooling conditions of the motors' generators by the oncoming airstream are at their maximum. An increase of the operating temperatures of the electrical machines or the use of coolants will be needed. To attain a higher operating temperature an interest is increasing for the machines of the type in which both windings (excitation and armament) are located on the stator, while the rotor is of the type of an inductor without a winding. These machines are 1.4 to 1.6 times heavier than the conventional ones.

During a fl ht speed corresponding to M=3 the available insulating materials are unfit for work, since their operating temperature is about 300°C. With M=2 in non-cooled partitions, the general purpose cables will be found under extreme operating conditions. With M=3 these cables are unusable, and another insulation with inorganic polymers will be required.

With the increase of the temperature, the resistance of the conductors rises. With M=3 the resistance of the copper conductor is doubled, which may result in an increase of the voltage of the power system, in order to decrease the cable weight.

The tendency to carry out the functions of regulation, control and protection at a low power level decreases the amount of heat, which has to be removed from the equipment. This lowers the operating temperature of the unit at the given temperature of the surrounding media.

The use of semi-conductors: diodes, transistors, and silicone rectifiers, switches, relays, and amplifiers, raises the reliability and improves the qualitative characteristics of aircraft electrical equipment.

Electrical relays are not completely excluded, even from the equipment now in the development stage, in connection with the fact that semi-conductors with the required characteristics are not available.

The electro-mechanical relay, inspite of a series of short-comings, possesses also a very quality owing to the presence of several conduct-pears isolated from one another. The coil is conveniently isolated from the conducts whereas the transistors or the control rectifiers require additional devices for attaining the required insulation.

Chapter II. Aircraft Power Supply With the Main D-C System.

1. Aircraft Power Supply from D-C Generators.

In fig. 2.1 and 2.2 we present the power supply systems for an aircraft, including the primary d-c 27 v power system, and secondary single-and three-phase a-c power systems.

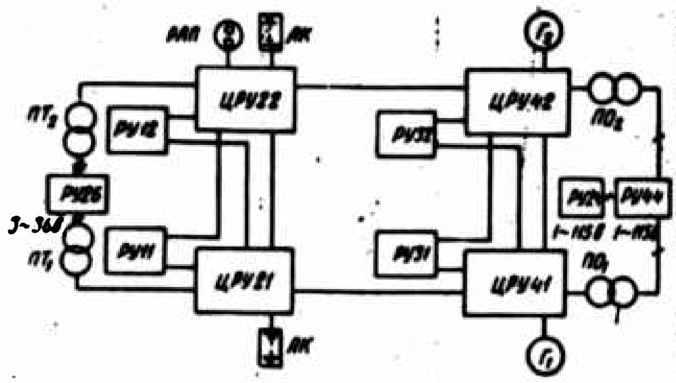

Fig. 2.1. Diagram of an aircraft system of power supply from 2 d-c generators.

In the primary power system the principal sources of energy are the starter-generators, which are activated by the aircraft engines The role of the auxiliary and emergency energy sources is fulfilled by the storage battery.

The most promising in these systems will be the use of the simplified circuit diagram of the d-c power system, with an angular, multichannel, protected feed power system, possessing a high reliability and vitality under normal and emergency operating conditions. The system maintains a working capacity in an extreme emergency situation, when all the generators have failed. In this case all the distributing busbars are automatically deprived of current, with the exception of the emergency busbars, from which the vitally important consumers indispensable for continuing the flight, if the aircraft engines are operating, or for landing if the engines have stopped, receive their power supply. In this situation, only the storage batteries serve as the energy sources.

Under ground conditions the aircraft system receives its feed from the airfield d-c source by means of an airfield contact rose.

The starter generator is used as the starter for the aircraft engine, receiving its feed from the ground source or from the aircraft's batteries. The electric power supply with single-phase alternating current with a voltage of 115 v ± 5% and a frequency of 400 cps ± 5% is carried out from the secondary power system, in which the energy sources are 2 convertors of the PO type, one of which operates and the other is in "cold" reserve and is automatically connected when the other one has gone out of commission. In diagram 2.2 there are 5 convertors, of which are the main and two are reserve convertors.

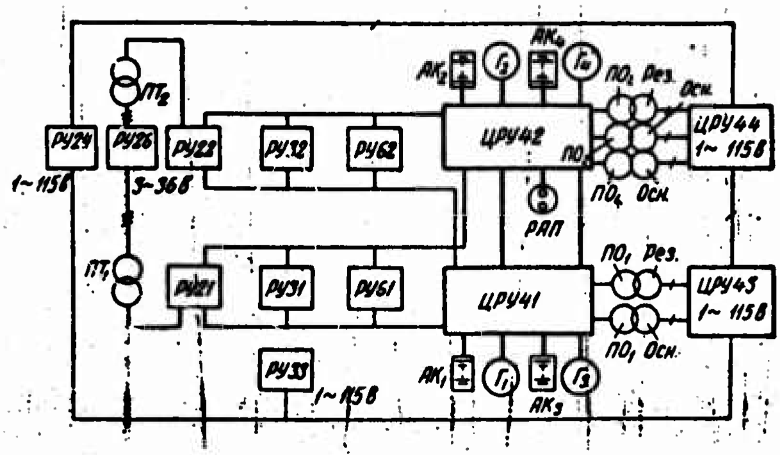

Fig. 2.2. Diagram of the power supply of an aircraft from 4 d-c generators.

The electric power supply with three-phase alternating-current with a voltage of 36 v ± 5% and a frequency of 400 cps ± 2%, is carried out from the secondary power system, in which the energy sources are 2 convertors of the PT type, one of which operates and the other is in "cold" reserve and automatically put into operation when the main one goes out of commission.

When the d-c generator fails, the convertors PO and PT are switched over to supplying the emergency power system, and are assigned the load of only the most important consumers with the minimum capacity.

2. Electric Power Supply of an Aircraft from D-C and A-C Generators.

In fig. 2.3 we present a system of electric power supply of an aircraft from four main d-c generators and four auxiliary a-c generators. The system consists of a primary d-c 27 v power system, an initial a-c power system, and secondary one-phase and three-phase a-c power systems.

In the primary d-c power supply system, the main energy sources are four starter generators, activated by the aircraft engines. The role of the auxiliary energy source is carried out by four batteries. The system operates analogously to the one examined in §1.

The primary, a-c three-phase power system with an unstable frequency and a voltage of 200/115 v is used for supplying consumers, which are indifferent to the frequency. The energy sources are four generators, activated by the aircraft's engines. The generators work separately for the corresponding groups of consumers. Upon the failure

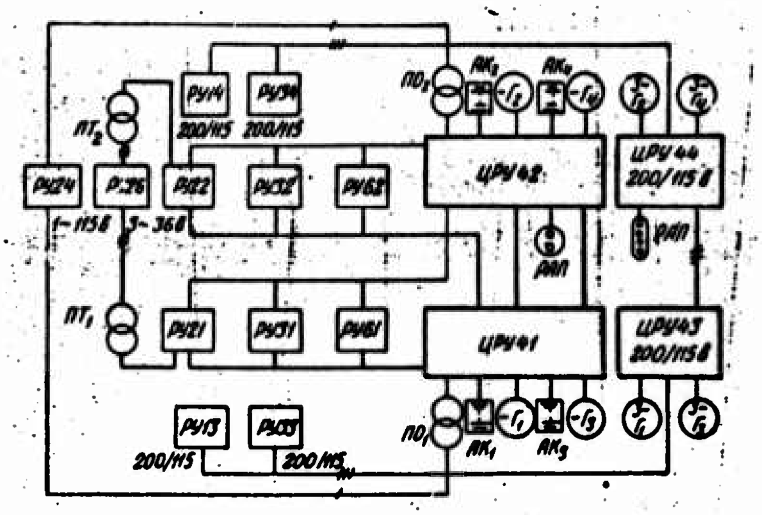

Fig. 2.3. Diagram of an electric power supply system of an aircraft from d-c and a-c generators.

of individual generators, the important consumers are switched over to be supplied from the remaining ones.

The electric power supply with single-phase alternating current and a voltage of 115 v ± 5% and a frequency of 400 cps ± 5% is carried out with the secondary power system with two conductors of the PO type, of which one operates and the second is in "cold" reserve and is automatically connected to the power system when the main one fails.

The power supply with a three-phase alternating-current, with a voltage of 36 v ± 5% and a frequency of 400 cps ± 2% is carried out by the secondary power system with 2 convertors of the PT, of which the first operates and the second is in the "cold" reserve and is automatically connected to the power system, when the main one fails.

In case of failure of the d-c generators, the PO and PT convertors are switched over to receive power from the emergency power system and continue to supply only the important, minimum capacity consumers.

Chapter III. Aircraft Power Supply With A Main Alternating-Current System.

1. Aircraft Power Supply from A-C Generators with Unstable Frequency.

ELECTRIC POWER SUPPLY SYSTEM. The principal primary power system is the three-phase a-c system with a voltage of 200/115 v with variable frequency and two a-c generators.

The secondary power supply system is a d-c 27 v system, in which the energy source is the transformer-rectifier unit (TRU).

The emergency power supply is produced by the a-c generator, which is activated by a wind-fan and from a small capacity battery.

For work on the ground an airfield a-c power source is used, connected through the airfield power supply rose APR. The power supply system is shown in fig. 3.1.

THE A-C POWER SUPPLY SYSTEM. The main source of the aircraft's power supply a-c system are two three-phase generators activated by the engine.

Each generator operates separately for a specific group of consumers. During normal work, generator G_1 supplies busbar E_1 and generator G_2 the busbars D and J.

If any one of the generators will produce a higher or lower voltage current, it is automatically disconnected from the busbar and the latter is connected to the generator in good order, and in the cockpit, a signal lamp lights up, indicating which of the generators is not operating.

Busbar Σ supplies a number of consumers, including the transformer-rectifying unit TRU_1.

Busbar E supplies a number of consumers including a 200/28 v transformer which delivers a 28 v alternating-current to busbar Z, from which the lighting equipment receives its power.

From the emergency busbar J, power is supplied to the vitally important consumers: the flaps system, the auxiliary pump, the airconditing system, the cockpit lighting, the position indicator, and the TRU_2.

The electric power supply system has minimum frequency relays which disconnect the busbars of both a-c generators, if the speed of revolution of the aircraft engines drops below 65%. In this case the work of all the electric power consumers ceases, with the exception of the auxiliary pump, which operates when the speed is reduced down to 40%.

In case of failure of both generators the emergency busbar J will receive its feed from the emergency a-c generator driven by the wind-fan, which in this case is moved out into the airstream. From busbar J through the emergency instrument feed transformer, the energy is delivered to busbar P of the instruments, from which the compass system and the position indicator are supplied.

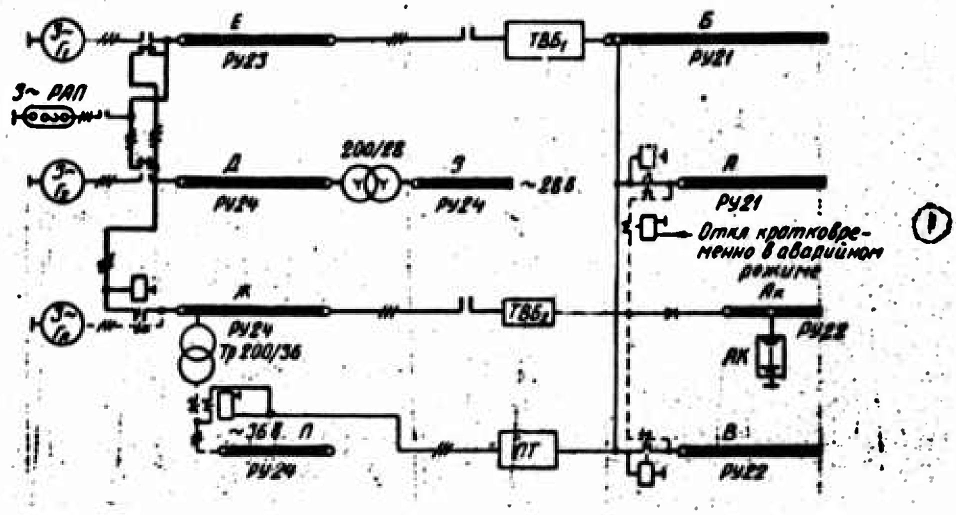

Fig. 3.1. Diagram of an aircraft electric power supply from two non-stable frequency a-c generators. Key: 1. Brief disconnection under emergency conditions.

When the air field feed source is connected to the aircraft power systems, the generators are automatically disconnected from the busbars, and all the free a-c busbars are converted to supply from the airfield source. In this case the protective relays disconnect the convertor PT from the main d-c busbar (in order to avoid its useless work) while the instruments are automatically switched over to receive their supply from the emergency a-c busbar through the instrument emergency feed transformer.

D-C FEED SYSTEM. During normal work the transformer-rectifier unit TRU_1 receiving its feed from busbar E, transforms the 200/115 v alternating-current into 28 v direct-current and delivers it to the main d-c busbar. A number of consumers, including the instrument feed convertor (PT) receive their power supply directly from this busbar.

During normal work, the emergency busbar A and the important consumer busbar C, supplying the units which assure flight safety, are connected to the main busbar B.

During normal work, the transformer-rectifier unit TRU_2, which receives its feed from the emergency a-c busbar J, delivers 28 v direct-current to the battery busbar AK and the battery, maintaining it all the time in the fully charged state.

In the case of failure of the main busbar B, busbars A and C are switched over automatically to receive their power from the transformer-rectifying unit TRU_2.

In case of failure of the main generators, the emergency generator delivers energy to the emergency busbar J from which the important consumers, including the TRU_2 receive their power supply.

In order to prevent over loading of the emergency generator, when the wing mechanisms are turned on (brief operating conditions) busbar A is automatically deprived of current.

In case all three generators fail, all the alternating- and direct-current busbars lose their current, with the exception of the battery busbar AK, which in this case receives its power supply from the battery. The blocking rectifier excludes the possibility of energy from the battery to the other busbars, which is indispensably in order to preserve the limited energy reserve of the battery. From the battery busbars the power is received by the systems of the fire alarm and generator failure signals, ignition, shut-off fuel valves and so forth.

The battery is the only independent source of direct-current in the electric system. The battery control is completely automated.

INSTRUMENT FEED SYSTEM. During normal work, the pilot's instruments are supplied with alternating-current from the the instrument feed convertor. The convertor, connected to the main d-c busbar P, converts the 27 v direct-current into 36 v alternating-current with a frequency of 400 cps and delivers it to the instrument power supply busbar P.

In case the convertor fails, busbar P is automatically connected through transformer TR to the emergency a-c busbar J, so that there is no interruption in the work of the instruments. Busbar P receives its power from J, even when the aircraft power system is connected to the airfield power supply.

CONCLUSIONS.

The power supply system provides reliably the power supply to the consumers of alternating- and direct-current. The quality of power with respect to its frequency is the best during the rated speed of revolutions of the aircraft engine and is maintained within the permissible limits within a small range of its speeds.

The power supply system with a non-stable frequency with 2 generators is usually employed in aircraft with one or two aircraft engines having a small range of revolution speeds. It can be used successfully in aircraft with several engines, its reliability increasing with the increase of the number of engines, generators, TRU, and PT.

2. Power Supply of an Aircraft during Separate Work of A-C Constant Frequency Generators.

THE POWER SUPPLY SYSTEM.

The basic primary power supply system is the three-phase a-c system with a voltage of 200/115 v and a constant frequency of 400 cps. The energy sources are three generators with a constant speed drive, operating separately for their respective groups consumers.

The secondary power supply system is the 27 v d-c system, the energy source of which consists of three transformer-rectifying units (TRU).

The 36 v alternating-current is produced from the basic current by means of transformers.

Emergency a-c power supply is obtained from the generator, installed on an auxiliary, self-contained unit, which is started in flight, when the principal generators fail.

The super-emergency d-c power supply is obtained from the battery and a-c power supply from the static convertor SP.

The ground power supply of the aircraft power system with alternating and direct currents is received from airfield energy sources by means of airfield feed roses AFR. The power supply diagram is given in fig. 3.2.

THE A-C POWER SUPPLY SYSTEM. The basic power supply system is the three-phase a-c constant frequency system, in which the energy sources are three a-c generators, activated by a hydraulic constant speed drive. The aircraft body is used as the power neutral. The power of the single-phase loads should not exceed 5%, which makes it possible to balance the generator phase loads.

THE CONSTANT SPEED DRIVE. On every aircraft engine, a differential hydraulic drive insuring the constant rate of revolution of the generator of 8000 rpm when the engine speed varies within the range of 3300 - 6400 rpm.

Under established operating conditions it assures the stabilization of the generators frequencies with a precision of ± 1%. During transient processes, that is, during changes in the rate of revolution of the engine or variations of the load, the frequencies may increase up to 5%.

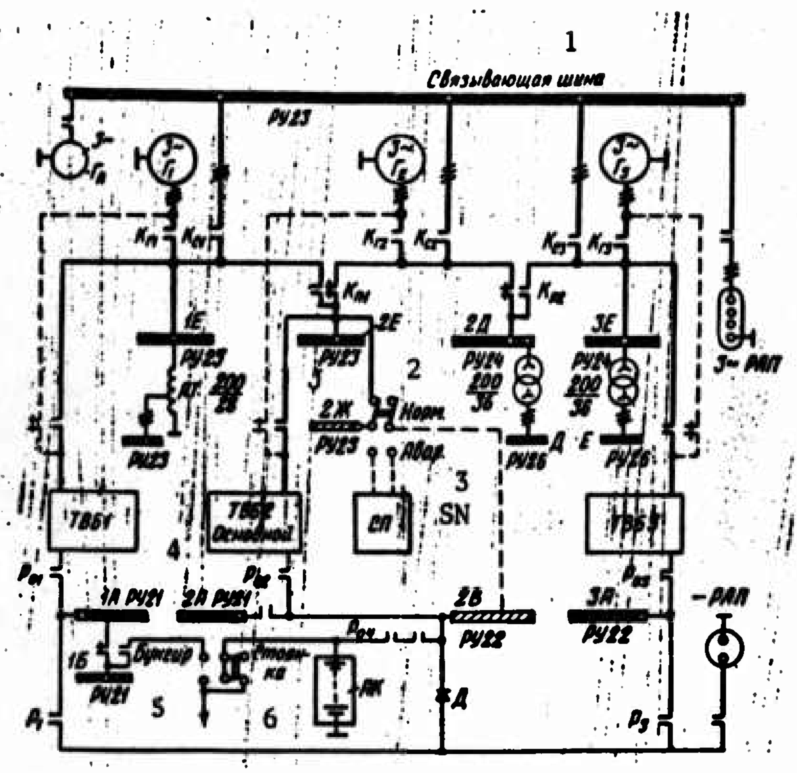

Fig. 3.2. Diagram of an aircraft power supply from three-phase a-c constant frequency generators.
Key: 1. connecting busbar, 2. normal, 3. emergency, 4. main, 5. towed, 6. parked.

The drive delivers the principal power by the mechanical method. The maximum power magnitude, transmitted hydraulically, amounts to not more than 20%. When the aircraft speed corresponds to the cruising flight conditions, the hydraulic drive pump carries practically no load.

Each drive is independent and has its own oil tank, cooler, oil temperature and pressure measurement instruments, and a system for protection against over heating. When the generator is damaged, the disconnection of the drive is provided for, but during flight it may not be reconnected again.

THE NON-CONDUCT A-C GENERATOR has a 6-pole rotating excitation winding with clearly expressed poles, which is supplied with power through the rectifier from the exciter.

During flight, the generator is cooled by the oncoming stream of air, on the ground the cooling air is delivered from the aircraft engine's compressor.

The full rated power is yielded by the generator under all conditions, including the work of the engine on the ground during low gas rpm.

The generator is protected against over heating by a mercury-switch, installed on the stator, which operates at a temperature of over 175°C.

THE GENERATORS'CONTROL PANEL. Each generator has its own control panel and provides voltage regulation and a protective system, which is made entirely of non-conduct elements. The voltage regulator under established conditions maintains the generator's voltage of 200 ± 4 v.

The panel provides protection of the electric power system from the following emergency conditions:

1. The over voltage protection system operates if the voltage exceeds 215 v during a time greater than 5 seconds. The time lag is necessary in order to exclude false operation of the protective system. If after the protective system has operated, the generator's voltage is restored to the permissible limits, it may be again turned on by the generator's switch, which at first is set up in the "off" position, and then into the "on" position.
2. The protective system against the voltage drop operates if the generator's voltage drops down to 185 v during 5 seconds. The repeated connection of the generator to the power system is provided for when its voltage rises to 186 - 195 v.
3. The protection against frequency excess disconnects the generator from the power system in case the frequency rises to 420-424 cps during 1 second. It is possible to reconnect the generator to the power system if the frequency drops down to 418-406 cps.
4. The protection against frequency drop operates when the frequency is 360-376 cps. When the frequency rises to 382-394 cps, we may again turn on the generator.
5. The protection against short-circuits and phase breaks is built on the principle of comparison of the non-balanced current, flowing through the control panel, with a balanced voltage.

Protection is provided against short-circuits only in the generator feeder up to the control panel. The primary power supply system (up to the distributing busbars) has no protective system. The wires of the primary feed system are installed in such a way as to exclude completely the possibility of short-circuits.

6. Protection against incorrect phase sequence.
7. Protection against over excitation and under excitation of the generators.

THE EMERGENCY A-C SOURCE consists of a small jet engine, on which the a-c generator is installed.

Under conditions on the ground, in the absence of airfield process of air and electric power supply, the unit supplies the air conditioning and the engine starting systems with air and the aircraft power supply system with electric energy.

THE STATIC CONVERTOR. On the aircraft, a static convertor of direct-current into alternating-current is installed, which is used for supplying the emergency instruments: the artificial horizon, the turn- and sleeping indicator, and certain radio-navigational instruments. It also provides electric power to the aircraft fueling system, which makes it possible to take on fuel for the aircraft using only the aircraft storage battery.

DISTRIBUTION OF A-C ELECTRIC ENERGY. The a-c generators of the main power system operate separately, each for its own load. During normal work the generator G_1 supplies the a-c busbar 1E, generator G_2 supplies the 2E and 2D busbars, and the emergency busbar 2J, to which the vitally important consumers are connected, which are required for completion of the flight under emergency conditions, and the G_3 supplies the 3E busbar.

The busbar of generator G_2 is divided into 2 parts, 2E and 2D, in order that in case one generator goes out of commission, the entire load would be distributed between the two remaining generators equally. The important duplicating electric energy consumers are divided between busbars 1E and 3E.

Under emergency conditions the loads are switched over in the following way. When generator G_1 is damaged, conductor G_1 is turned off and the generator is disconnected from the power supply line. At the same time, conductors K_{c1} and K_{c2} and the switch-over conductor $K_{\Pi 2}$ operate. Busbar 1E is connected to generator G_2, and busbar 2D will be switched over to receive its power supply from generator G_3.

When generator G_2 is damaged, conductor K_{c2} is turned on, and conductors $K_{\Pi 1}$ and $K_{\Pi 2}$ are switched over. In this case, busbar 2E, is connected to generator G_1 and busbar 2D to generator G_3. When generator G_3 goes out of commission, conductor K_{c3} is turned off, conductors K_{c2} and K_{c3} are turned on, and the conductor $K_{\Pi 1}$ is switched over. Busbar 3E is thus connected to generator G_2, and busbar 2E is switched over to receive its feed from generator G_1.

Upon failure of any two generators, busbars 1E and 2E, or 2D and 3E are supplied with a-c feed. The emergency a-c busbar J is supplied either from busbar 2E or from the static convertor. The load between the busbars is distributed in such a way, that upon failure of two generators, the aircraft can continue its flight under any conditions.

When the airfield a-c feed source is connected, the connecting conductors K_{c1}, K_{c2}, and K_{c3} operate and supply feed to all the a-c busbars. The control of the frequency, voltage, and phase sequence of the airfield a-c feed source is provided for. The airfield source is connected to the aircraft power system only in case if all the above mentioned parameters are within the permissible limits.

When the principal engines are started, the connecting conductors are automatically turned off, and the generators are connected to supply their own busbars.

The emergency a-c feed source is connected to the power supply system in the same way as the airfield feed source. A blocking system is available, which does not permit the parallel work of the airfield and emergency supply sources. In this case only the emergency supply source is connected to the power system. The blocking system also prevents the parallel work of the main generators and the emergency supply source. In this case, the preference is given to the main generators.

In case of failure of the automatic a-c switch-over system, a manual system with three switches is provided. In case of failure of any constant speed drive or generator, the corresponding signal lamp lights up, informing the crew of the damage and indicating which switch should be used for switching over the busbars. The switches are installed in such a way, that it is impossible to throw more than one switch simultaneously.

The prolonged load of each generator practically does not exceed 50% of the rated power of the generator. Therefore, when one generator goes out of commission, the two remaining generators fully provide the power supply for all the loads. Upon failure of two generators, a part of the loads is disconnected by the busbar switch-over circuit diagram. A brief 5 minute load is supplied through the overload capacity of the generator.

THE A-C SUPPLY SYSTEM WITH A VOLTAGE OF 27 v is an auxiliary (secondary) power supply system, in which the energy sources are three transformer-rectifying units (TRU) of three kw each. Direct-current is mainly used for supplying radio-equipment, conductors, relays, signal lamps, etc. In spite of the large quantity of d-c electric circuits, the ratio of the d-c power consumed to the a-c power used, is approximately 1 : 10.

The rated load of a unit is 110 A. Two units may operate in parallel and supply a 160 A load for a long time.

During the rated work, the d-c 1A, 2A, and 3A busbar are supplied each from its own TRU. Units 1 and 3 may operate in parallel. The main one is unit 2, because it supplies with power the d-c emergency busbar 2B, to which the vitally important power consumers are connected. In the circuit of unit 2 there is a blocking diode D, which permits the power supply to busbar 2A and emergency busbar 2B from units 1 and 3, not permitting the feeding of busbars 1A and 3A from unit 2.

When one unit goes out of commission, all the busbars may receive their power supply from the remaining two.

In the feeder of every TRU a reverse current relay P_0 is installed, which during a short-circuit at the output site of the unit disconnects it from the system. The reverse current relay, provided on the storage battery feeder, upon a short-circuit at the terminals and inside the battery disconnects it from the power system.

There is a contact rose for connecting the aircraft power system to the airfield d-c feed source, which provides the power supply for all the d-c consumers.

An auxiliary switch "parking-towing" is installed, which delivers from the battery the power supply for certain consumers: communications, pressure monometer of the braking system, and navigational illumination of low intensity. During parking only the low light intensity navigational illumination is supplied with power.

EMERGENCY D-C POWER SUPPLY. As the emergency d-c power source, a lead-acid storage battery with the capacity of 25 Ah is used. When all the three a-c generators go out of commission, the battery supplies power to: communications, navigational instruments, illumination of the pilot's instrument panel, illumination of the passenger cabin, and a static convertor, which supplies the emergency a-c instruments. The battery provides power to emergency loads for 30 minutes. It also assures three startings of the emergency feed unit, under normal atmospheric conditions. Under ground conditions, the battery may be charged for a long time from the emergency feed unit, or from the airfield a-c power source, through the transformer-rectifying unit.

3. Aircraft Power Supply During the Parallel Work of A-C Constant Frequency Generators.

POWER SUPPLY SYSTEMS.

The power supply system consists of a primary a-c power system with a voltage of 200/115 v with a constant frequency of 400 cps ± 1% and a secondary 27 v d-c power system.

The principal electric power sources are four three-phase a-c generators with a power of up to 40 kwA, which are activated by the aircraft engines to a constant speed drive.

The constant speed generator drives are independent hydraulic systems.

The 27 v direct-current is obtained from the alternating-current by means of four transformer-rectifying units with a power of 1.5 kw each. These storage battery has a capacity of 36 Ah and supplies a-c energy to certain control elements when the power systems are first undone, and also supplies vitally important consumers under emergency flight conditions.

All the a-c energy is distributed through the central distributing system directly for the consumers and the secondary distributing devices, installed in the crew's cabin.

The feed on the ground is delivered in the form of three-phase alternating-current from the airfield source. The general diagram of the power supply system is given in fig. 3.3.

The energy from the generator is delivered to the corresponding generator busbars, into the central distributing system (CDS 16), which is the primary distributing point in the system. The CDS contains the principal busbars, generator connection conductors, synchronization busbar conductors, airfield feed conductors, and other equipment, intended for control and protection (current transformers and relays). The generator conductors K_g connect the generators to the main busbars, where K_c connect them for parallel work.

The energy from the main CDS busbars is transmitted directly to certain consumers, and to the secondary distributing devices DD, located in the crew's cabin and other compartments of the aircraft. One part of the energy from the secondary distributing devices is transmitted directly to the three-phase and single-phase consumers, the other is stepped-down by the transformers to 28 v and is used for lighting. A part of the alternating-current is converted by the transformer-rectifying units into 28 v direct current, and used for supplying d-c consumers.

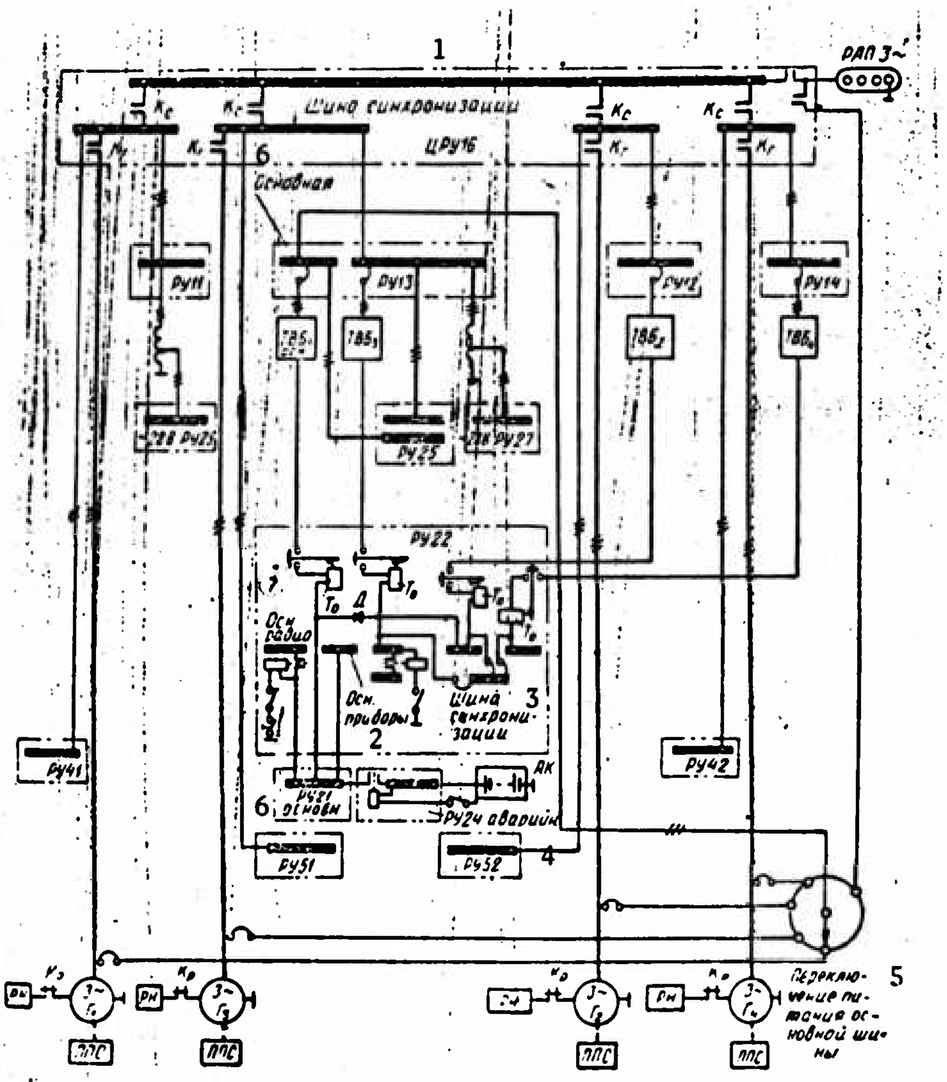

Fig. 3.3. Diagram of an aircraft power supply from four a-c constant frequency generators.
Key: 1. synchronization busbar, 2. principal instruments , 3. synchronization busbar, 4. emergency, 5. switching-over of the main busbar feed, 6. main, 7. main radio.

THE A-C SYSTEM is the principal power supply system, which delivers power to all the consumers, including consumers indispensable for the safety of aircraft and crew. The energy sources are four non-conduct generators, each of which has its own control and protective system. Normally, the generators operate in parallel, supplying three-phase alternating-current to all the consumers simultaneously. However, the loads are distributed in such a way, that each generator would supply its own individual busbar, isolated from the other generators, which may at that time operate either in parallel or separately.

To the main a-c busbar located in DD13, the energy is delivered directly from the output of the generator independently on the normal distribution system. To supply the main busbar with energy, any generators or airfield electric power source may be selected.

The generators may be controlled manually by switches from the control panel in the crew's cabin, turning off the main automatic devices. To each generator correspond three switches. The "generator control" switch controls the action of relay (K_p), which connects the excitation winding of the generator with the voltage regulator. The "synchronization contact" switch controls the action of the synchronization conductor K_c, which is normally turned on. The "generator conductor" switch controls the action of the generator conductor K_g.

Since the synchronization conductors are normally turned on, when any "generator conductor" switch is turned on the energy is delivered to all the four busbars of the CDS. The conductors, upon being switched on, convert automatically the generators to parallel work. All three switches for each generator with three positions are kept in the middle position "off" by springs. When the switch is set in the "on" or "off" position, the corresponding contact or relay operate. The actual position of the conductors or relays is shown by the signal lamp "circuit open" for conductors of the generator and synchronization, and their signal lamp "off" for the generator conduct relay.

THE AIRFIELD A-C SOURCE through the contact rose, the airfield feed conductor and synchronization conductors is connected to the distributing busbars of the generators. The circuit excludes the possibility of parallel work of the airfield source and the generators. All the four conductors of the generators are automatically opened befor the airfield feed conductor is turned on. The turning on of any generator conductor automatically opens the airfield feed conductor. The airfield feed switch has three positions "on", "off", and "airfield service". In the latter case the energy is delivered only for servicing the airplane and goes to the main busbars.

THE A-C GENERATOR is a non-contact, three-phase generator, with a capacity of 40 kwA with a power neutral and a rotating excitation winding. The generator is excited from the a-c exciter through the three-phase full wave rectifier, located on the generator rotor shaft.

The generator is cooled with an airstream, created by the aircraft engine compressor. A thermo switch is installed into the main generator's stand.

AUTOMATIC CONTROL AND PROTECTION of the a-c system is carried out separately by control panels for each generator. When the generator switches are turned on, the panel automatically sends signals to the generator's conductors, control relays, and parallel work conductors. Each panel protects automatically the corresponding generator system either by isolating it if the generator works in parallel with other generators, or turns off the generator. The blocking relays in the panel, which protect the control relay of the generator and the parallel work conductor against closing, should operate only in the presence of faulty operation.

THE CONSTANT SPEED DRIVE is an independent fluid drive system, and in the case of faulty operation, it is disconnected from the aircraft engine.

THE 27 VOLT D-C POWER SYSTEM is used for feeding the control relays and conductors, of various signalling devices, electric cranes, and other consumers.

The energy sources are four non-regulated transformer-rectifier units (TRU) with capacities of 1.5 kw each.

Units 2, 3, and 4 operate in parallel through the special synchronizing busbar. The main unit 1 operates only for its own busbars. The other three units through the blocking diode D, when necessary, supply auxiliary power to the main unit 1 feeder, which is especially important when the latter fails.

The reverse current T_0 relays protect against the possibility of passage of the energy into the faulty TRU from the TRU in good order.

All the TRU are supplied with power from specific a-c busbars. The main unit 1 may obtain its feed directly from the terminals of any generator or the airfield source, when the switch is set up in the appropriate position; a special switch is used for switching over.

The system provides for a storage battery for 36 Ah. The storage battery may be charged from the main unit 1 and from others, through diode D.

In case of failure of all the TRU the storage battery supplies the main busbar, providing d-c energy to consumers, which are required for the controlling functions.

The system provides for full wave rectifiers, connected for each phase for 115 v. This d-c energy is used for supplying the connection roses, located in restrooms and in the pilot's cockpit.

4. Aircraft Power Supply from Two-Independent A-C Constant Frequency Systems.

The entire supply system is divided into two independent electrical systems A and B, which under normal conditions operate in complete isolation from one another. The diagrams of the power supply systems are given in fig. 3.4 and fig. 3.5.

The principal primary power system is the three-phase a-c, 200/115 v system, with a constant frequency of 400 cps. The energy sources are four non-conduct a-c generators, which are activated by fluid constant speed drives.

As a role, a-c systems operate separately, however, it is possible to join them by a special conductor K, in order to eliminate the overload of a generator, when one of the two generators working in parallel fails.

The energy from the generators is delivered mainly to the distributing busbars, from which certain consumers receive their feed directly, and secondary distributing busbars. The secondary busbars receive their feed over a single-channel radial protected system, which assures the required reliability under the conditions of short lengths and good protection against damage of the power supply lines.

In order to increase the reliability, we resort to sectioning the secondary busbars, which are supplied over independent channels from various primary busbars.

In order to lighten the load of the rectifying units, to feed part of the consumers, a low voltage alternating-current is used, which is drawn from the automatic 200/28 v transformers.

To assure the flight of the aircraft upon the failure of all four engines an emergency turbine generator is provided, which is activated by a wind-fan. In this case the a-c energy is used only for supplying the vitally important units and the reserved transformer-rectifying unit (TRU).

THE SECONDARY POWER SYSTEM is a d-c 27 v system, in which the energy sources are two transformer-rectifier units (TRU).

The d-c power systems also form two independent systems, in each of which a rectifying unit and a storage battery operate in parallel.

Provisions are made for a reserve rectifying unit, which may be used for replacing any, that has gone out of commission. The reserve unit is the primary source of direct-current, when the emergency a-c turbine jet generator is operating.

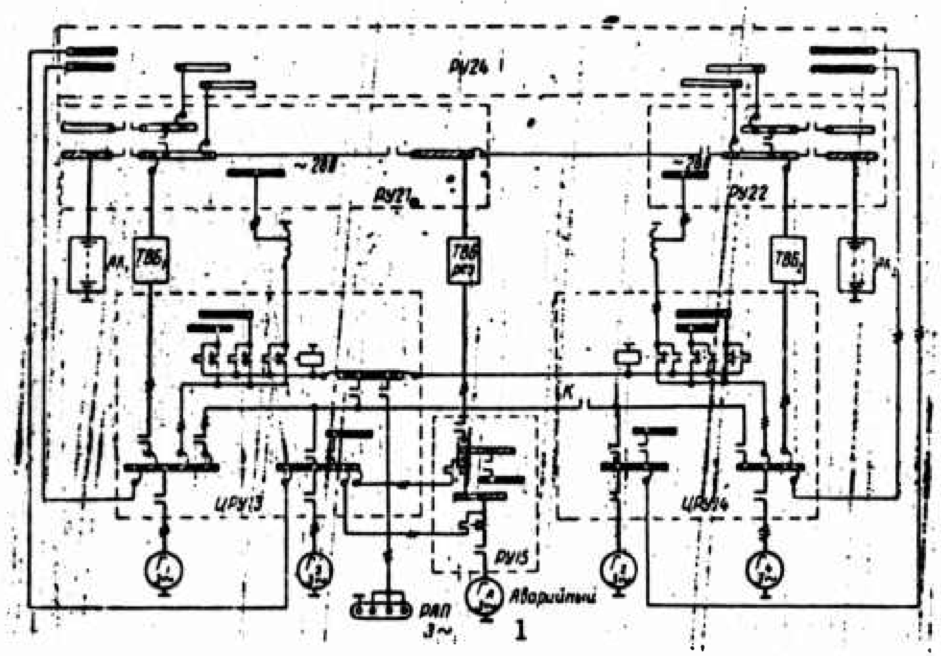

Fig. 3.4. Diagram of an aircraft power supply from two independent a-c constant frequency systems.
Key: 1. emergency.

When the latter fails, the only sources of energy are the storage batteries, which supply power to the especially important consumers, required for a brief flight and landing.

Provisions are made for a ground feed source of a three-phase alternating-current only.

5. Aircraft Power Supply with a Combined Circuit Diagram of A-C Constant Frequency Generators.

POWER SUPPLY SYSTEM

The power supply system consists of a primary three-phase a-c power system with a voltage of 200/115 v and a constant frequency of 400 cps $\pm$ 1%, and a secondary 27 v d-c power system.

The principal energy sources are four non-conduct three-phase alternating current generators, which are activated by constant speed drives, which are independent pneumatic systems.

The d-c 28 v power sources are four transformer-rectifier units (TRU).

The auxiliary d-c sources are four batteries, which assure, the starting of the turbine unit, the supply of the controlling elements in specific periods, and are the emergency sources when all the four a-c generators fail.

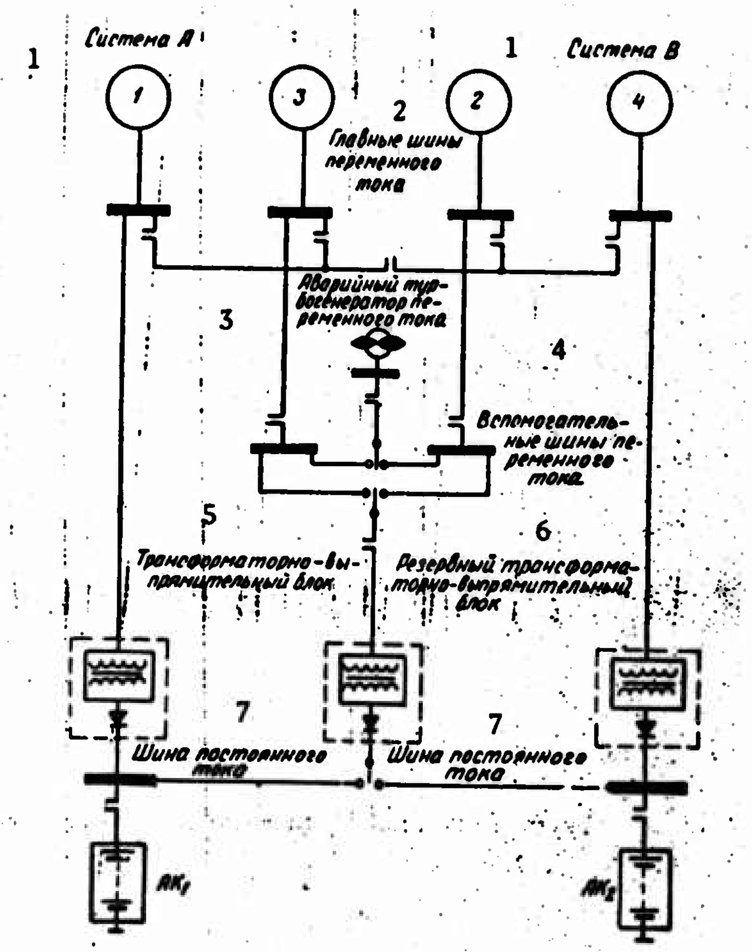

Fig. 3.5. Simplified circuit diagram of the electric power distribution.
Key: 1. system A, system B, 2. main alternating current busbars, 3. emergency a-c turbo generator, 4. auxiliary a-c busbars, 5. transformer-rectifier unit, 6. reserve transformer-rectifier unit, 7. direct-current busbar.

All the a-c energy is distributed through the main busbars of the two central distributing systems CDS43 and CDS 44. From the main busbars, power is received by certain consumers directly as well as secondary distributing devices, located in the crew's quarters and other compartments, where specific consumer groups are concentrated.

The system provides for ground power supply with a three-phase alternating- and direct-currents.

The general diagram of the power supply system of the aircraft is shown in fig. 3.6.

THE A-C POWER SYSTEM. Generators normally operate in parallel, combined through the synchronization busbar and supply alternating-current to all the consumers. However, the loads are distributed in such a way, that each generator will be able to supply its own main busbars, isolated from the other generators.

The power system provides for three operating conditions:

1. Parallel work of four generators.
2. Separate work of two groups with parallel work of two generators in each group.
3. Separate work of generators for a corresponding group of consumers.

The energy from the generators is delivered to the main distributing busbars of the generators into the central distributing systems CDS43 and CDS44, which are the primary distributing points in the system. In the CDS the main busbars are located as well as the synchronization busbars, generator connection conductors, airfield feed and emergency generator conductors, and other equipment, intended for control and protection.

The energy from the main busbars of the CDS is transmitted to the secondary distributing devices DS and directly to a number of consumers.

The secondary distributing busbars are fed radially from the corresponding primary busbars over three channels with two-sided protection.

A part of the a-c energy is delivered to the three- and single-phase consumers without any changes. A part of the energy is converted by the three-phase transformers into a lower voltage of 36 v and by automatic transformers into a 28 v and lower voltage. A certain part of the alternating-current is converted into d-c 28 v current, by means of transformer-rectifying units.

With separate work, each generator supplies power to a certain group of consumers and is loaded by not more than 0.5 of its rated capacity. A damaged generator is automatically disconnected from the network, and its consumers are also automatically switched over to the working generator, the latter being loaded only to the rated capacity.

Each generator may be controlled manually by means of two switches. One of them turns on the generator for parallel or separate work. One common switch for all the four generators makes it possible to prescribe parallel work conditions for all four generators or for two in a group.

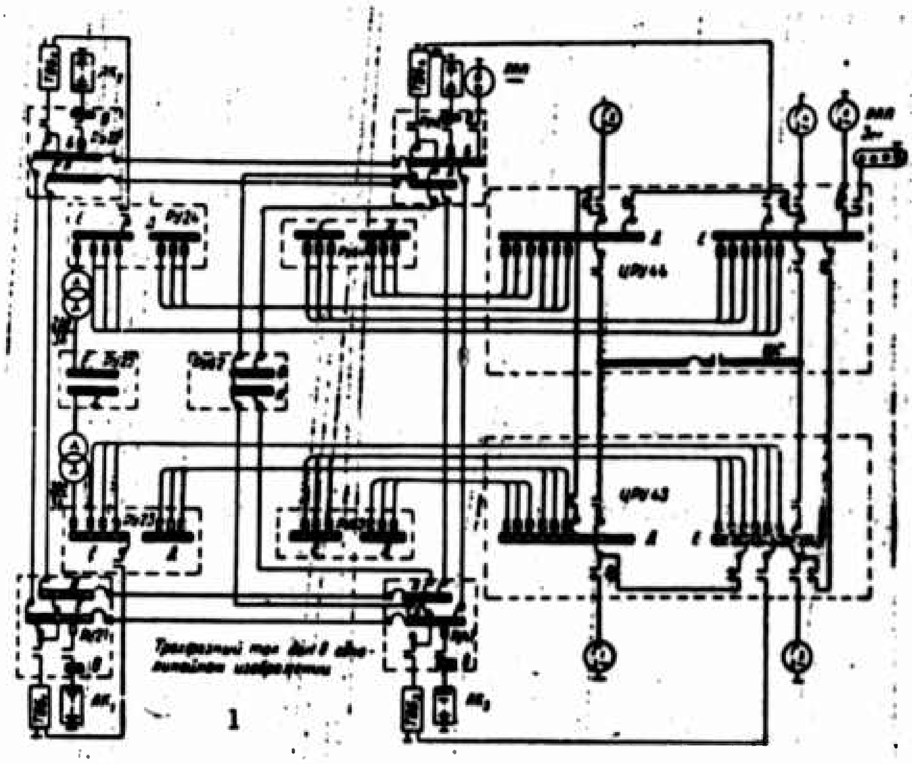

Fig. 3.6. Diagram of an aircraft power supply system with a combined system of connection of the a-c constant frequency generators.
Key: 1. three-phase current is shown as a single line.

AUTOMATIC CONTROL AND PROTECTION of the a-c system is carried out by the corresponding units, separate for each generator.

THE POWER SUPPLY FROM THE AIRFIELD IS DELIVERED in the form of alternating-current. A special blocking excludes the possibility of parallel work of generators and the airfield source.

A 27 VOLT D-C POWER SYSTEM is used for supplying control-low-power electric motors, electric cranes, instruments, signalling, and individual lighting feeder circuits.

The energy sources are four non-regulated transformer-rectifier units (TRU). The units operate in parallel for a common two-channel energy ring. With the uniform distribution of the load on the busbars each rectifier operates for its own CDS busbars, and in the connecting wires between the CDS flows an insignificant equalizing current, which increases only when any one unit fails. The secondary distributing devices are supplied over a four-channel ring system, with a two-sided wire protection.

The reverse current relay disconnects the TRU from the power system when it is damaged. The system provides for four storage batteries, which during flight may be charged from the power system.

Upon the failure of the rectifiers, the batteries supply their own busbars C, in which energy is received by some principal consumers indispensable for controlling and piloting functions.

Two TRU are supplied with power from the primary distributing systems, and the two others from secondary distributing devices.

The separation of a d-c power system into two independent systems is not shown in the diagram, but it can be carried out with conductors, as it is shown in fig. 2.17 of the sixth section.

APPENDIX: An Example of Development of a Rough Draft of a Passenger Airplane.

As an example we shall examine the development of a rough draft on the electrical equipment of a medium weight passenger airplane.

The development of a draft begins with the examination of the customer's requirements, selection of equipment, and determination of the electric energy consumers.

The consumers are grouped with respect to functions and put down into a table, a possible variation of which is shown in table 1. The capacities of the consumers are presented in the corresponding columns, depending on the length of the work and the type of current required.

The low power consumers are not entered in the table with the exception of those which require a high voltage or frequency precision.

According to the table data, we determine the ratio between the powers with respect to the type of current, voltage, and frequency, establish the primary and secondary power systems, determine the powers and number of energy sources and plot load schedules.

In the example under examination, according to the consumers' capacity ratios, with respect to the type of current, taking into account the advantages of using electric starters for starting the aircraft engines, it is advisable to adopt as the primary power system the d-c power system with a secondary single-phase and secondary three-phase a-c energy.

In accordance with this, we developed the basic electrical diagrams of the power systems and the consumers, with respect to their functions.

If in the initial planning stage the advantages of the use of a certain type of current as the main one, are not obvious, then it is advisable to develop in parallel two power systems with the primary constant and alternating-currents in order that, upon the development of the basic consumer systems, we will be able to render more precise the operational and weight characteristics, and select the best power supply variations.

The technical documents are filled out in accordance with the above mentioned principles.

In fig. 1 we give the simplified diagram of a primary d-c power system, the principal source of which consists of four starter generators with a capacity of 12 kw each, and the auxiliary sources are two storage batteries with capacities of 30 Ah each.

The energy sources are selected from the condition of the maximum possible power of simultaneously connected consumers, taking into account the required reserves.

The generators and equipment are shown only for the left side, opening up the internal systems of the single set.

The consumers' feeders in the distributing devices are grouped with respect to functions. The protective system is not shown, but the true values of the current consumed are given. Brief loads are marked with index "k".

The value of the true currents makes it possible to determine easily the cross-sections of the wires supplying the distributing device's busbars, select the type and rated value of the protective system. Next to the name of the wire, we show the initial and calculated data: length, cross-section, value of the current passing through it under the most difficult conditions, and the voltage loss in this wire.

The numeration of the units is carried out in accordance with the functional classification in the range between 100 and 199. The figure is the denominator of the unit and shows the section (control board) in which it is installed.

For the sake of simplicity we do not show the numeration of the wires in fig. 1, and it is carried out in work planning, according to the previously described rules.

The presence of the system of distribution of the units, the CDS, the AD, and the communications of the conductors, gives us a complete concept of the lay-out of the power system on an aircraft.

The presence of a table with the indication of the unit's weight, design, and wires, makes it possible to determine the installed and flight weight of the power system.

In the sixth section* in fig. 1.9, we show the simplified diagram of the secondary power system of a single-phase alternating-current, the sources of energy of which are two convertors of the PO type, with a capacity of 1500 vA each. One of them operates, and the second is in "cold" reserve and is connected when the main one goes out of commission.

In the sixth section* in fig. 1.12, we show the simplified circuit diagram of the secondary three-phase alternating-current power system, the energy sources of which are two convertors of the PT type with a capacity of 750 vA each. One of them works and the other is in "cold" reserve and is automatically connected when the main one goes out of commission.

In fig. 2 we show the simplified electrical diagram of aircraft control system. The simplified electrical diagrams of the consumers for other functions are made similarly.

In the development of the simplified electrical diagrams, the capacities and operating conditions of the consumers, for various stages of flight are rendered more precisely. The final data on the consumers are recorded in tables with which the load schedules of the energy sources are rendered more precise. The tables and curves are made separately for each type of current.

As an example, for the d-c consumers of the entire aircraft were made table 2 and accordingly plotted a load curve, presented in fig. 3. The curve reflects the loads which are common for the entire aircraft. Analogously we form the tables and plot load curves separately for each busbar and distributing device.

On the basis of the load schedule, according to the heaviest regime, we determine the maximum capacity of simultaneously connected consumers. The heaviest flight regime from the point of view of the value of the load for each specific aircraft is established on the basis of the thorough analysis of the nature of the consumers' work. For a passenger aircraft, this would be the night flight with a maximum connection of the heating elements, lighting, and passenger facilities.

*The rough draft of the above mentioned diagram should be supplemented with technical data as it is shown in fig. 1.

Table 1: Table of Electric Energy Consumers

Таблица потребителей электрической энергии

Функции		Потребители		Мощность одного потребителя вт (ва)						Число потребителей	Коэффициент одновременности	Суммарная мощность одноименных одновременно работающих потребителей																		Примечание
					Однофазный переменный		Трехфазный переменный					Обязательный род тока															Род тока безразличен вт (ва)			
												Постоянный вт			Однофазный переменный f=400 гц ±5% ва			Однофазный переменный f=var ва			Трехфазный переменный f=400 гц ±2% ва			Трехфазный переменный f=var ва						
№	Наименование	№	Наименование	Постоянный ток	f=400 гц	f=var гц	f=400 гц	f=var гц	Род тока безразличен			5 сек	5 мин	длительно	5 сек	5 мин	длительно	5 сек	5 мин	длительно	5 сек	5 мин	длительно	5 сек	5 мин	длительно	5 сек	5 мин	длительно	
5	Двигательные системы	1	Расходомер	5	50					2	1			10			100													
		2	Масломер	32						2	1			64																
			Итого											1328			100													
6	Управление самолетом	1	Механизм закрылков	2700						2	1		5400																	
		2	Механизм стабилизатора	1000						2	1		2000																	
		3	Триммер руля поворота	48						1	1	48																		
			Итого									100	8000	235																
7	Тепловые системы	1	Механизмы наддува кабины	81						2	1	162																		10% от времени полета
		2	Механизмы противообледенителя	81						6	0,5	240																		
		3	Обогрев стекол			700				4	0,75									2100										
			Итого									500		180						2100										
8	Приборное оборудование	1	Указатель поворота	10	100		50			1	1			10			100						50							
		2	Навигационная система	108	100					1	1			108			100													
			Итого											1300			250						300							
9	Автоматическое оборудование	1	Автопилот	600	200		250			1	0,5			300			100			125										
			Итого											400			100			125										
10	Освещение	1	Освещение салонов						10	40	0,75																		300	
		2	Освещение отсеков						10	20	0,5																		100	
		3	Фары						108	4	0,5																	216		
			Итого																										1128	

(Table of Electric Energy Consumers, continued)

Продолжение

Функции: №	Функции: Наименование	Потребители: №	Потребители: Наименование	Мощность одного потребителя вт (ва): Постоянный ток	Однофазный переменный: f=400 гц	Однофазный переменный: f=var гц	Трехфазный переменный: f=400 гц	Трехфазный переменный: f=var гц	Род тока безразличен	Число потребителей	Коэффициент одновременности	Суммарная мощность одноименных одновременно работающих потребителей. Обязательный род тока. Постоянный вт: 5 сек	Постоянный вт: 5 мин	Постоянный вт: длительно	Однофазный переменный f=400 гц ±5% ва: 5 сек	5 мин	длительно	Однофазный переменный f=var ва: 5 сек	5 мин	длительно	Трехфазный переменный f=400 гц ±2% ва: 5 сек	5 мин	длительно	Трехфазный переменный f=var ва: 5 сек	5 мин	длительно	Род тока безразличен вт (ва): 5 сек	5 мин	длительно	Примечание
11	Сигнализация 37	1	Габаритный огонь						81	4	1																		324	
		2	АНО 38						108	4	1																		432	
		.	 39																											
			Итого																										1116	
13	Радиооборудование 40	1	41 Связная радиостанция	1080	430					2	0,7			1513			600													
		2	Командная радиостанция 42	650	215					2	0,7			910			300													
		.	. . . .																											
			Итого											[illegible]			1750						300							
14	Бытовое оборудование 43	1	Кипятильник 44						540	8	0,125																		540	
		2	Духовой шкаф						1080	2	0,5																		1080	
		3	Подогрев воды буфета						297	4	0,25																		297	
		.	. . . .																											
			Итого																										8400	
15	Топливная система 45	1	Насосы подкачки						810	4	1																		3240	С перерывами по 30 *мин* 48
		2	Насосы перекачки						810	4	0,75																		2430	
		.	46																											
			Итого											8010			75												5356	
			47 Суммарная мощность									600	8000	13283			2275			2225			600						16000	
			49 Суммарная мощность с учетом коэффициента одновременности работ											10600			1820			1780			480						12800	

1. Functions.
2. Consumers.
3. Capacity of 1 consumer's watts (wA).
4. Total power of similar simultaneously operating consumers.
5. Mandatory type of current.
6. Direct, watts.
7. Single-phase alternating.
8. Three-phase alternating.
9. Type of current in different watts (vA).
10. Remarks.
11. Name.
12. Name.
13. Direct current.
14. Single-phase alternating.
15. Three-phase alternating.
16. Type of current, indifferent.
17. Number of consumers.
18. Simultaneity factor, 11-5 sec., 12-5 min., 13-prolonged, 14-5sec., 15-5 min, etc., etc., 16-engine systems, 17-fuel meter and oil-meter, 18- total.
19. Aircraft control.
20. Flap mechanism.
21. Stabilizer mechanism.
22. Rotor trimmer.
23. Heating systems.
24. Cabin ventilation mechanism.
25. De-icer mechanism.
26. Heaters.
27. 10% of the flight time.
28. Instrument equipment.
29. Turn indicator.
30. Navigational system.
31. Automatic equipment.
32. Automatic pilot.
33. Lighting.
34. Passenger cabin lighting.
35. Compartment lighting.
36. Headlights.
37. Signalling system.
38. Outside dimensions lights.
39. Navigational lights.
40. Radio equipment.
41. Communication radiostation.
42. Command radiostation.
43. Utilities.
44. Water boiler, 2) oven, 3) kitchen water heater.
45. Fuel system.

46. 1) auxiliary pumps, 2) pumping over pumps.
47. Total power.
48. With 30 minute brakes.
49. Total power, taking into account the work simultaneity coefficient.

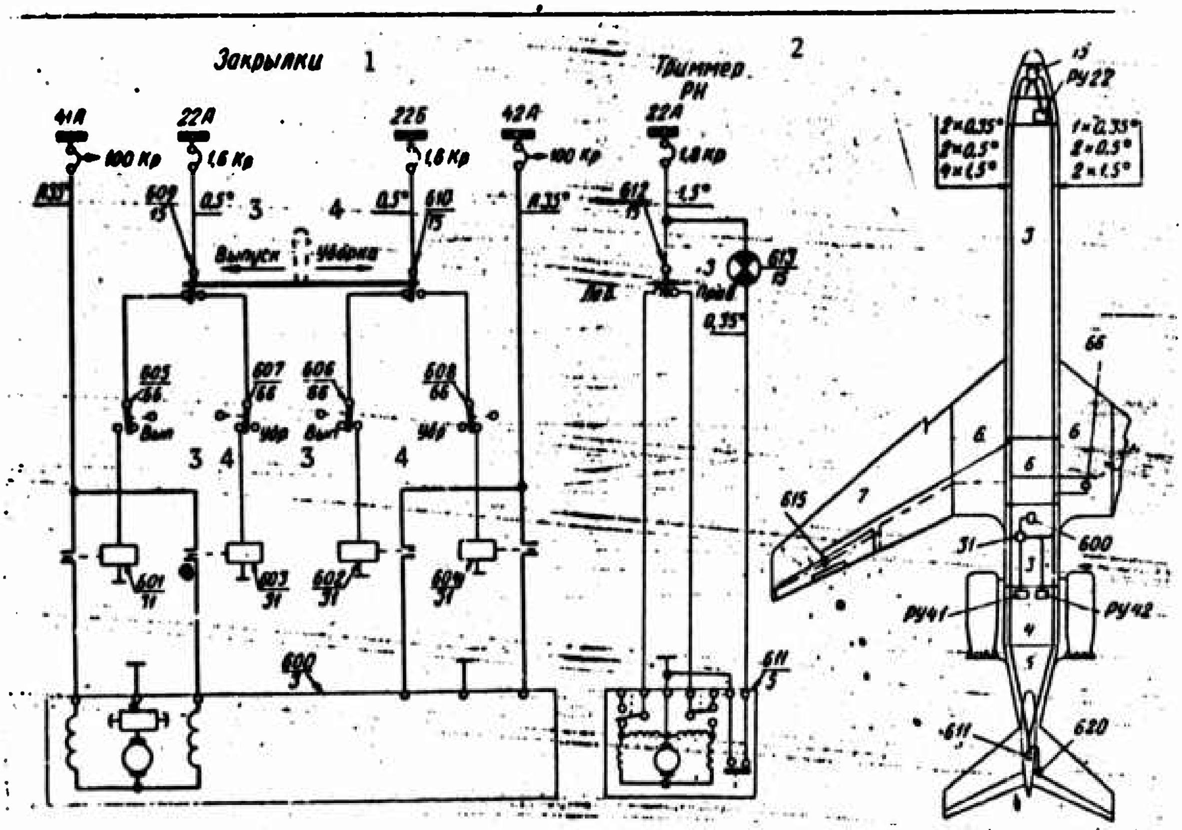

Fig. 2. Simplified electrical diagram of aircraft control system. Remark: The electrical diagrams of the aileron trimmer control (positive 7-615) RV (positive 5-620) are similar to the RN trimmer.

Key: 1. flaps, 2. RN trimmer, 3. let out, 4. pick up.

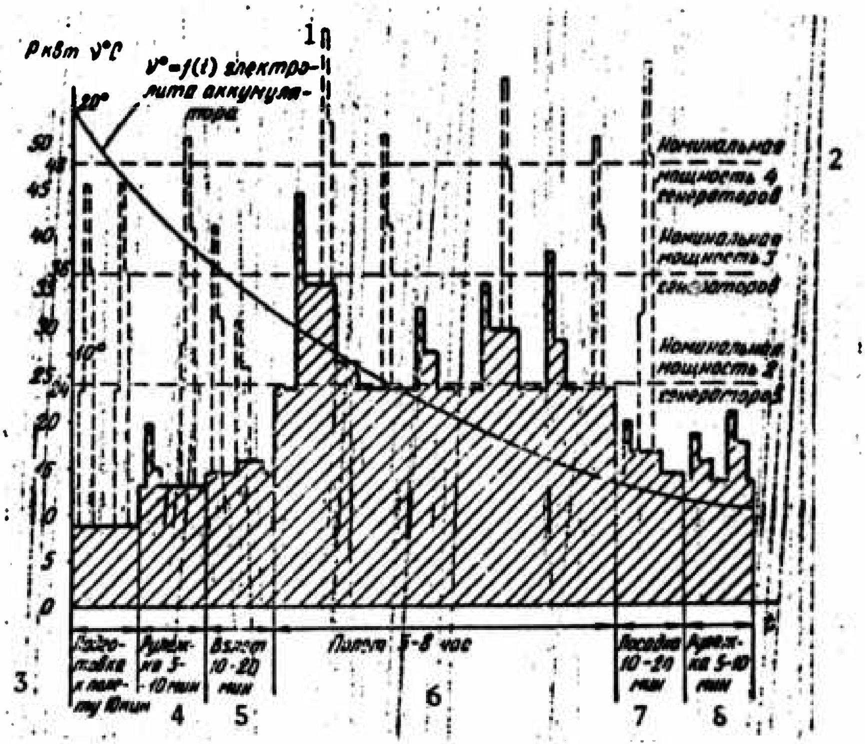

Fig. 3. Load schedule for d-c sources.
Key: 1. of battery electrolyte, 2. rated capacity of four generators; rated capacity of three generators; rated capacity of two generators; 3. flight preparations, 4. taxiing 5-10 min., 5. take-off 10-20 min., 6. flight 5-8 hours, 7. landing 10-20 min., 8. taxiing 5-10 min.

Taking into account the simultaneity coefficient of switching on the consumers, the discharge state of the storage batteries during starting, and the indispensable power reserve in case of failure of one of the two generators, their number and capacity are determined. For any given aircraft, these conditions are satisfied with four generators of 12 kw each, which assure a power reserve of about 100%. Brief overloads lasting 5 seconds or 5 minutes are provided for through the overload capacity of the generators and storage batteries.

The load schedule is plotted for the static operating conditions of the consumers according to their rated capacity. If the consumers capacity during the operating cycle is non-uniform, then we should take the root mean square value of the power which is required to satisfy only the consumers of medium and high capacity.

The storage batteries are selected in relation to their purpose. In the aircraft examined, the storage batteries fulfill the following functions:

Table 2: Table of D-C Electric Energy Consumers.

1 Функции		2 Потребители		Мощность одного потребителя, *вт* 11	Число потребителей 12	Коэффициент одновременности 13	Суммарная мощность одноименных одновременно работающих потребителей по этапам полета в *вт* 3																	
							4 Подготовка к полету			5 Рулежка			6 Взлет			7 Полет			8 Посадка			5 Рулежка		
9 №	Наименование	№	10 Наименование				до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно
1	Энергетика постоянного тока 17	1	18 Преобразователь ПО-1500	2800	2	0,5	14	15	16			2800			2800			2800			2800			2800
		2	Преобразователь ПТ-750	1670	2	0,5						1670			1670			1670			1670			1670
		. . .	. . . .																					
			20 Итого						600			5000			6000			7000			6000			5000
5	Двигательные системы 19	1	Расходомер	5	2	1						10			10			10			10			10
		2	Масломер	32	2	1						64			64			64			64			64
		. . .	. . . .																					
			21 Итого						1100			1100			1100			1300			1200			1300
6	Управление самолетом 22	1	Механизм закрылков	2700	2	1					5400			5400						5400				
		2	Механизм стабилизатора	1000	2	1								2000			2000			2000				
		3	Триммер руля поворота	48	1	1	48			48			48			48			48			48		
		. . .	 23																					
			Итого						100			100			100			200			100			100
7	Тепловые системы 24	1	Механизм наддува кабины	81	2	1	162			162			162			162			162			162		
		2	Механизмы противообледенителей	81	6	0,5										243			243					
		. . .	25																					
			Итого						170			170			170			180			170			170
8	Приборное оборудование 26	1	Указатель поворота	10	1	1						10			10			10			10			10
		2	Навигационная система	108	1	1						108			108			108			108			108
		. . .	27																					
			Итого						1000			1000			1000			1000			1000			1000

Table 2 continued

Функции		Потребители		Мощность одного потребителя в *вт*	Число потребителей	Коэффициент одновременности	Суммарная мощность одноименных одновременно работающих потребителей по этапам полета в *вт*																	
							Подготовка к полету			Рулежка			Взлет			Полет			Посадка			Рулежка		
№	Наименование	№	Наименование				до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно
9	Автоматическое оборудование	1	Автопилот	600	1	0,5									300			300			300			
28		. . .	. . . . . 29 .																					
			Итого						100			100			400			400			400			100
10	Освещение	1	Освещение салонов	10	40	0,75			300			300			300			300			300			300
		2	Освещение отсеков	10	20	0,5			100															
		3	Фары	108	4	0,5					216									216				
30		. . .	. . . . . . 31 .																					
			Итого						1200			1200			1200			1100			1200			1200
11	Сигнализация	1	Габаритный огонь	81	4	1					324			324							324			324
		2	АНО	108	4	1			432			432			432			432						
32			33																					
			Итого						500			800			1000			800			800			800
13	Радиооборудование	1	Связная радиостанция	1080	2	0,7						1512			1512			1512			1512			1512
		2	Командная радиостанция	650	2	0,7			910			910			910			910			910			910
34		. . .	35																					

Table 2 continued

Функции		Потребители		Мощность одного потребителя в *вт*	Число потребителей	Коэффициент одновременности	Суммарная мощность одноименных одновременно работающих потребителей по этапам полета в *вт*																		
							Подготовка к полету			Рулежка			Взлет			Полет			Посадка			Рулежка		
№	Наименование	№	Наименование				до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно	до 5 *сек*	до 5 *мин*	длительно
			Итого						600			1700			1700			1700			1700			1700
14	Бытовое оборудование	1	Кипятильник	540	8	0,125												540						
		2	Духовой шкаф	1080	2	0,5												1080						
		3	Подогрев воды буфета	297	4	0,25												297						
36		.	37																					
			Итого															8000						
15	Топливная система	1	Насосы подкачки	810	4	1						3240			3240			3240			3240			
		2	Насосы перекачки	810	4	0,75						2430			2430			2430			2430			
38		.	. . . . 39 . .																					
			40 Итого						5200			5200			5200			8000			5200			5200
			Потери в сети						500			881			903			1313			901			883
			Суммарная нагрузка по всем системам 41						10570			16370			17870			29680			17770			16470
			Суммарная нагрузка с учетом коэффициента одновременности 42						8450			13100			14300			23800			14200			13200

1. Functions.
2. Consumers.
3. Total capacity of identical simultaneously operating consumers with respect to flight stages in watts.
4. Flight preparation.

5. Taxiing.
6. Take-off.
7. Flight.
8. Landing.
9. Name.
10. Name.
11. Capacity of a single consumer, watts.
12. Number of consumers.
13. Simultaneity coefficient.
14. Up to 5 seconds.
15. Up to 5 minutes.
16. Prolonged.
17. Direct-current engineering.
18. PO-1500 convertor, 2) PT-750 convertor.
19. Propulsion systems.
20. Flow-meter, 2) oil gauge.
21. Total.
22. Aircraft control.
23. flap mechanism, 2) stabilizer mechanism, 3) rotor mechanism.
24. Heating systems.
25. Cabin regulation system, 2) de-icing mechanisms.
26. Instrument equipment.
27. turn-indicator, 2) navigational system.
28. Automatic equipment.
29. Auto-pilot.
30. Lighting.
31. Passenger cabin lighting, 2) compartment lighting, 3 head lights.
32. Signalling equipment.
33. Outside dimension lights, 2) navigational lights.
34. Radio equipment.
35. Communication radio station, 2) command radio station.
36. Facilities.
37. Water boiler, 2) oven, 3) kitchen water heater.
38. Fuel system.
39. Auxiliary pumps, 2) pumping over pumps.
40. Losses in the power lines.
41. Total load for all the systems.
42. Total load taking into account the simultaneity coefficient.

1. They provide for the self-contained starting of the aircraft engines.

2. They supply the consumers with electric energy during the partial flight preparation.

3. During flight they cover the load peaks.

4. They serve as the reserve energy source when the generators fail in flight.

5. They supply energy through the radio stations during a forced landing.

In order to select a storage battery, we tentatively prescribe its type and check its capacity from the point of view of meeting the load curve. During calculations, the initial capacity of the battery is taken at 70% of the rated capacity, and the residual capacity by the end of the flight should be not less than 20-22% of the rated capacity. The battery's capacity, lost during a discharge, and the capacity obtained in the charging process, is calculated with formulas given in section IV. The data for calculations are conveniently entered in table 3. For this type of aircraft we selected two storage batteries of the 12-SAM-28 type with capacity of 28 Ah each, and accordingly check the required capacity taking into account 4-5 aircraft engine starts; the residual capacity in this case should not be less than 20% of the rated.

Similarly we plot the load schedules for the single-phase and three-phase alternating current.

Parallel with the work of the main power systems and lay-out of the equipment, a general diagram is created for arranging the principal units and communications of the electrical equipment conductors. The diagram is drawn on the two basic projections of the aircraft with separate outside details of the characteristic unit arrangement groups, blocks and passages through places crowded to capacity with other equipment. A specially thorough work over to the places were the possibility of damage to electrical equipment is the most probable, is given.

Table 3.

1	2	3	4	5	6	7	8	9	10
№ этапа полета	Продолжительность этапа полета	Характер работы (разряд, заряд)	Средняя величина тока разряда	Расходуемая емкость разряда	Температура электролита	Остаток емкости от предыдущего этапа в % к номинальной	Приведенная номинальная емкость аккумулятора при заданных токе и температуре	Величина отданной или полученной емкости в % от номинальной	Остаточная емкость к концу этапа в % от номинальной

1. Number of flight stage.
2. Length of flight stage.
3. Nature of work (discharging, charging).
4. Mean value of current discharge.
5. Discharge capacity expanded.
6. Electrolyte temperature.
7. Remainder of capacity from the previous stage in % of the rated capacity.
8. Reduced rated capacity of the battery with a prescribed current and temperature.
9. Delivered or received capacity value in % of the rated.
10. Residual capacity at the end of a stage in % of the rated.

After carrying out the graphic and calculating works, a brief description is made in which the working principle of the systems, main electrical parameters, design and operating features are reflected.

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13. ABSTRACT

The author describes the possible variations of aircraft electric power systems. He discusses the merits and faults of types of current, generators, equipment, conductors, drives. Numerous circuit diagrams show how to avoid catastrophy in case of failure of individual power sources, lines, convertors, etc. The most promising types and systems are recommended. An example of a draft of an airplane's power system is given.

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