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CHARACTERISTICS OF OPERATION OF 400 HZ FREQUENCY (OSOBENNOSTI R--ETC(U)
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CHARACTERISTICS OF OPERATION OF 400 Hz FREQUENCY ELECTRIC ENERGY SYSTEMS*

by V. S. Zhemoydo, G. I. Kitayenko, and L. N. Tokarev

Today it is apparent that the use of 400 Hz frequency electric energy systems (EES) on small-tonnage fast vessels produces effective results. A number of river boats, as well as one of the first sea-going vessels -- the controllable hydrofoil passenger motorship TAYFUN -- are being successfully operated with this type of electric energy systems. This as yet little experience permits making a deduction that the expectations of improvement of the overall weight indices, as well as simplification and improvement of other characteristics of the systems resulting from higher current frequency have been justified.

However, some specialists in marine electrical technology raised the question of complications in certain operating phases of the 400 Hz frequency electric energy systems as compared to the conventional systems. In particular, doubts were expressed regarding the chance of steady parallel operation of 400 Hz frequency generators because of possible difficulties with synchronization. Doubts were also expressed regarding automation of electric power plants; automatic equipment and systems were

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* Full translation of the original article.

not available; opinions differed on problems of frequency adjustment and stability of operation of automatic load distribution systems; some concern was caused by high reactances of certain types of generators; and the possibility of generating 400 Hz frequency electric energy of the required quality appeared to be debatable.

It was only natural, therefore, that designers of fast small-tonnage ships rightly demanded that all of these problems be resolved. It has now become possible to generalize certain phases of work that have been completed and to answer the above questions. The present article, however, does not deal with the volume and weight indices of machines, prime movers, distribution equipment, transformers, and so forth, since they have already been discussed in sufficient detail /for example in the book "Sudovyye elektroenergeticheskiye sistemy povyshennykh parametrov (Higher Parameter Marine Electric Energy Systems)" by G. I. Kitayenko, L. 1970/.

<u>The Quality of 400 Hz Frequency Electric Energy.</u> Voltage drop in generators when connected to a load is determined, as we know, by the values of transient and sub-transient reactance of the generators (x_d' and x_d''). For 400 Hz frequency generators, these values differ significantly depending on their type. Thus, for generators S, G, and SM type, x_d'' is approximately 0.25, 0.16, and 0.12 per-unit ohms, respectively. For comparison, for 50 Hz frequency machines of equal power, $x_d'' = 0.14$ per-unit ohms. That is why there is the difference in the voltage drop of some specific 400 Hz frequency generating sets under a purely inductive

load. As is known, the voltage drop is determined from the formulas

$$\frac{x_d'}{x_d' + x_v} > \Delta U > \frac{x_d''}{x_d'' + x_v}$$

After a variation in the load, voltage recovery for 400 Hz frequency generators is several times faster than for conventional ones. Whereas for 400 Hz frequency type S generators it is approximately 0.07 sec, for M type 50 Hz frequency generators it is about 0.25 sec. Today instead of an electromagnetic corrector, a semiconductor corrector is used in the voltage regulator of S type generators, which makes it possible to use it as a shaft generator. When its rotative speed varies by ± 10-15%, the voltage now varies by not more than ± 3% of the nominal.

Candidate of technical sciences V. N. Tolcheyev recorded under laboratory conditions a phenomenon that is unusual compared to prevalent conclusions. Application of a thyristor automatic voltage regulator made it possible to reduce by almost half the value of the initial voltage variation of the generator (at the moment of connecting the load) by very rapid forcing of voltage excitation. The voltage drop was thus reduced from 25% to 15%. The outlook for such improvement of voltage regulators is obvious.

The accuracy of regulating the frequencies of generator sets with higher parameters is not yet very high, because the system of combined speed control has not yet found practical application. The development of combination gas turbogenerator regulators that would ensure control accuracy under static operating conditions not lower than ± 3% and a maximum frequency deviation when connecting and disconnecting a 100% load of not more than 1.5 - 2.0% of the nominal, holds great potentials for solving this problem. The block diagram (Fig. 1) shows a gas turbogenerator (G and GT), fuel equipment (RS), electromagnet (EM), amplifier (U_{em}) which operates the electromagnet, active current transducer (DN_1) for generating the speed regulator signal conforming to the load, active current transducer (DN_2) for automatic distribution of the active load, load distribution amplifier (U_{sd}), frequency transducer (DCh) for generating the frequency control circuit by deviation (SD) -- servomotor.

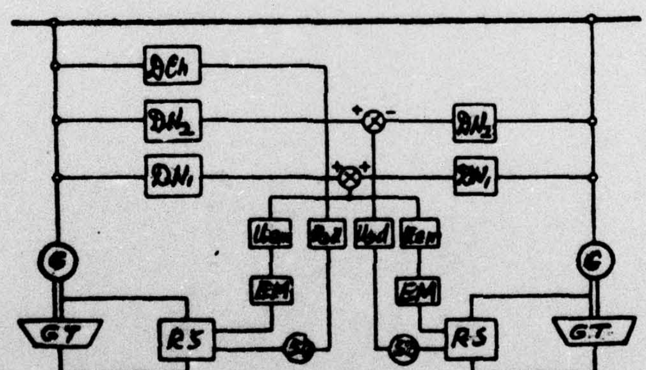

Fig. 1. Block diagram of a gas turbogenerator automatic frequency regulator.

Such a control system ensures not only frequency stabilization by its astatic characteristics, but also automation of the process of reception and distribution of the active load.

Furthermore, frequency adjustment of the generators prior to synchronization is automated; at the same time, the quartz type reference generator of the frequency transducer is disconnected and instead, the frequency voltage with which synchronization is effected is connected for comparison. In the latest regulator designs, an all-electric integrator-servomotor replaces the electro-mechanical one. All control system components are structurally integrated as a single unit and are supplied with turbogenerators. The dynamic qualities of the system are illustrated by an oscillogram (Fig. 2,a) which shows how the rotative speed varies when a 100% active load is connected. For comparison

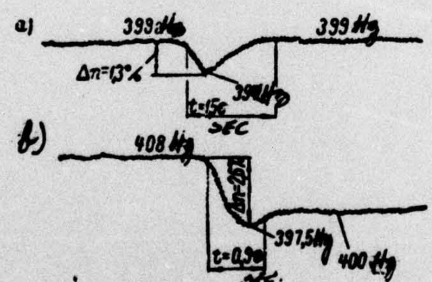

Fig. 2. Effect of control circuit on the transient process according to the load.

(Fig. 2,b) depicts the process of rotative speed variation with the load without control circuit. It is apparent here how greatly the quality of the electric energy improves in its frequency as a result of application of a combination speed regulator.

Parallel Operation of Generating Sets With Higher Parameters. As is known, the basic physical feature of their parallel operation is that at one and the same relative value of the difference of the rotative speed of generators operating in parallel (in percent), the velocity of the relative angular displacement of the voltage vectors of 400 Hz frequency machines is eight times greater than that of conventional ones. This circumstance made some specialists doubt if there was sufficient stability in the parallel operation of higher frequency generators. However, the results of experimental and theoretical investigations demonstrate that basically for all generating sets used in shipbuilding the stability margin is practically the same for both frequencies. The experiments were carried out with parallel operation of 20 to 75 kw diesel-driven generators and gas turbogenerators. Considerable experience has also been accumulated with parallel operation of high-frequency transformers in a 1 to 250 kw capacity range. On the basis of these data, it may be assumed that a changeover to higher frequency will not lead to unstable operation of generating sets.

All of the foregoing, however, has no relation to those specific cases of parallel operation where power swings occur between the generators. Thorough investigations have shown that such swings are caused by nonlinearities of a "free-play" type generating either in the speed regulators of a prime engine, or in the voltage regulator correctors of the generators proper. Essentially, these nonlinearities generate oscillations in the same manner at both frequencies, and the methods of their attenuation are the same, irrespective of the frequency.

When designing 400 Hz frequency marine electric power plants with units having combination (double impulse) speed regulators, one must take into consideration the need for equalizing connections between the regulators in order to ensure stable load distributions with parallel operation.

Problems of Synchronization of 400 Hz Frequency Generators. In model simulation of operating conditions of generating sets having the same parameters, but of different frequency, curves can be derived characterizing variation in relation to time of the angle δ between the rotor axes of the machines being synchronized. The mode of the transient process depends on the number of oscillations of an angle δ and the value of the first deviation. If we continue to read oscillograms with higher frequency values (above 400 Hz), the synchronization will soon become unstable, which indicates unsteady oscillations of the synchronous machines in relation to one another. Transition to stabilizing oscillations is shown as phase trajectories of the oscillation process (Fig. 3) in the coordinates "slip (s) -- angle (δ)" at two values of the reactor resistance (x_p). Prior to paralleling, the slip of the machines was equal to 0.65%; after that, two oscillation cycles close to the value of an angle $\approx$ 40° took place and only in the third cycle did the movement of the phase trajectory towards the limiting (steady) cycle of natural oscillations begin (Fig. 3,a). One of the basic reasons for increase in the first deviation of angle δ with frequency rise is that with one and the same difference in the kinetic energy of the generating sets, rotating before being connected for parallel operation at different speeds, the time in which equalizing of the kinetic energies should take place diminishes. Apparently, the shorter this time, the greater must be the moments to be applied to the shafts of the synchronous machines for rapid braking of one, and acceleration of another. Unstable synchronization occurs in a case where in order to reduce the difference in the kinetic energies of the generating sets it is necessary to have a maximum moment and correspondingly an angle which exceeds considerably its limiting value at stable parallel operating conditions.

Curves of dependence of the limiting difference of the frequencies on the resistance of the reactor which limits the inrush current (Fig. 4) can be obtained in the following manner. In an experimental setup, the required frequency difference between the line and generator is given, after which synchronization is performed across a reactor of some specific value. If the synchronization is successful, the difference in the frequencies increases, and the generator is connected again to parallel operation with the line. In this manner the value of the initial slip was derived above which synchronization is unstable, and below which it is stable. The experiments were repeated for several values of the reactor's resistance. One of the curves (I) was

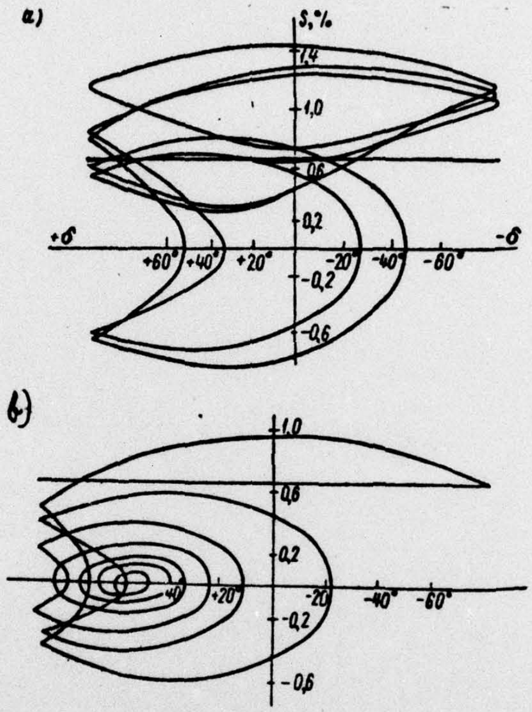

Fig. 3. Phase trajectories of the synchronization process:

a -- with x_p = 2.0 per-unit ohms, s_o = 0.65% (unstable process);

b -- with x_p = 1.5 per-unit ohms, s = 0.65% (stable process).

the result of synchronization of a 100 kw, 50 Hz frequency diesel--driven generator, and the other (II) -- of a 40 kw, 400 Hz frequency gas turbogenerator. The corresponding design curves are plotted with the aid of formulas

$$s_{cr.1} = \frac{1}{x_p k_s};$$

$$s_{cr.2} = \frac{1}{\sqrt{2\pi f\ T_a x_p}}$$

where s_{cr} -- is the critical slip, per-unit ohms;

x_p -- is the reactor resistance, per-unit ohms;

k_s -- is the amplification coefficient of the generating set speed regulator (value inverse to the statism of the regulating characteristic);

T_a -- is the inertial constant of the set;

f -- is the generator frequency.

The least of the value $s_{cr.1}$ and $s_{cr.2}$ is selected.

The current value of the 400 Hz frequency generators connected for parallel operation (as with 50 Hz) is calculated either from the simplified formula

$$I = \frac{\sqrt{2}\, k_y}{x''_{d1} + x''_{d2} + x_p} \sin\frac{\delta}{2}.$$

where k_y -- is the impulse coefficient;

δ -- is the initial angle between the rotor axes;

x''_d -- is the subtransient reactance of the generators, --

-- or from the exact formula derived from the Gorev-Park equations

$$i_{d1} = \frac{(1-\cos\delta)(x_p + x''_{q1} + x''_{q2})\cos\delta - (x_p + x''_{d2} + x''_{q1})\sin^2\delta}{(x_p + x''_{d1} + x''_{d2})(x_p + x''_{q1} + x''_{q2})\cos^2\delta + (x_p + x''_{q1} + x''_{d2})(x_p + x''_{d1} + x''_{q2})\sin^2\delta};$$

$$i_{q1} = \frac{(1-\cos\delta)(x_p + x''_{d1} + x''_{q2})\sin\delta + (x_p + x''_{d1} + x''_{d2})\sin\delta\cos\delta}{(x_p + x''_{d1} + x''_{d2})(x_p + x''_{q1} + x''_{q2})\cos^2\delta + (x_p + x''_{q1} + x''_{d2})(x_p + x''_{d1} + x''_{q2})\sin^2\delta}.$$

The second system of formulas produces a more precise result with a considerable difference in the subtransient resistances along the longitudinal and transverse axes (x''_d and x''_q).

Graphic Solutions of Synchronizers. Development of 400 Hz frequency electric power plants required the utilization of other systems and synchronization principles, different from the ones used for conventional frequency systems. The basis for this was as follows:

The principle of exact synchronization with constant time-advance can only be applied at strictly sine beat voltage of the machines being synchronized prior to connection to parallel operation. For this, the speed of the generating sets must be maintained at a very high degree of stability (up to hundredths of a percent), otherwise the beat voltage will not be sinusoidal. Such requirements are caused by the fact that the frequency difference of the 400 Hz generators prior to being connected must be not more than 0.1 ÷ 0.15% (as a comparison, -- at 50 Hz frequency, it may be 8 times greater). Application of this principle at a 400 Hz frequency requires also some make-time automatic device of not more than 0.03 - 0.05 sec. However, the existing automatic devices suitable for application in electric power plants of small displacement ships do not as yet meet these requirements.

For the immediate future there are, in the authors' opinion, two versions of solving the problem of synchronization of 400 Hz frequency generators: application of a synchronizer

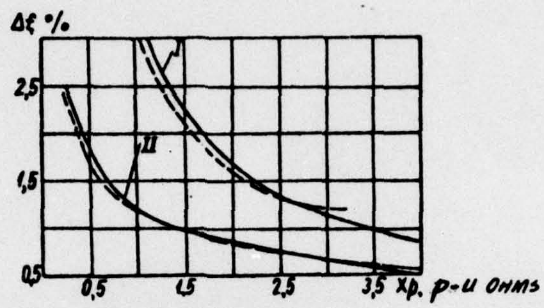

Fig. 4. Dependence of critical frequency difference on the resistance of a reactor during synchronization (design curves are shown by broken line).

(I -- synchronization of 50 Hz frequency diesel-driven generators; II -- synchronization of 400 Hz frequency gas turbogenerators).

with a constant lead angle and fast acting contactor connected for the duration of the synchronization in parallel with the generator's automatic controller; or synchronization across a fairly low resistance reactor with a limited closing angle. In the latter case, in order to expand the zone of synchronization stability, a transducer of active current going through the reactor and acting upon the prime mover regulator may be added to the circuit. Both versions, when tested experimentally, demonstrated high efficiency.

There are no basic difficulties in matching the frequencies of generators with higher parameters. To illustrate this, let us refer to an experiment with automatic matching not only of the frequencies, but also of phases of two generating sets equipped with transducers of voltage frequency and phase differences.

Through the amplifiers, the transducers affected the speed regulators of the generator driving engines, not only matching the frequencies, but equalizing the phases as well (Fig. 5).

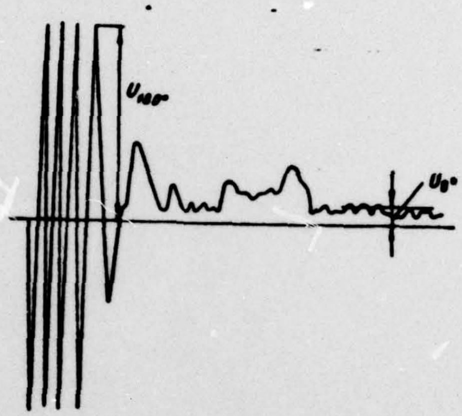

Fig. 5. Oscillogram of the process of regulation of the angle between the direction vectors of type GPCh-12/400 generators.

Prior to connecting of the devices, the generators were rotating with a fairly large slip in relation to one another; after the devices had been connected, in approximately three seconds, the frequencies and phases were equalized to an accuracy of up to 20 electric degrees.

<u>Automation of 400 Hz Frequency Electric Power Plants.</u> At the present time all the equipment has been developed that ensures the automation of matching and stabilizing frequencies, synchronization, load distribution, and so forth.

Automation of 400 Hz frequency electric energy systems is simplified by the fact that gas turbogenerators will be supplied complete with the automatic equipment (only the logic circuits of operation of automatic machines and devices for connecting the reserve and unloading will not be included). On the other hand, it is precisely on small tonnage ships that it is more convenient to start a transition to the next stage of automation of 400 Hz frequency systems -- automatic control by the energy users to meet the varying operating regimes of the entire ship. Transition to selective control, which opens the way for extensive application of micromodules, is the same for the systems of automation of 400 Hz frequency electric power plants.

CONCLUSIONS.

Theoretical and experimental-design work accomplished thus far permits designing modern automatically controlled 400 Hz frequency electric energy systems for small tonnage ships. In spite of certain difficulties in maintaining the operating conditions of these systems due to higher parameters, in their technical performance and ease of operation they will be no less efficient than similar 50 Hz frequency systems.

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