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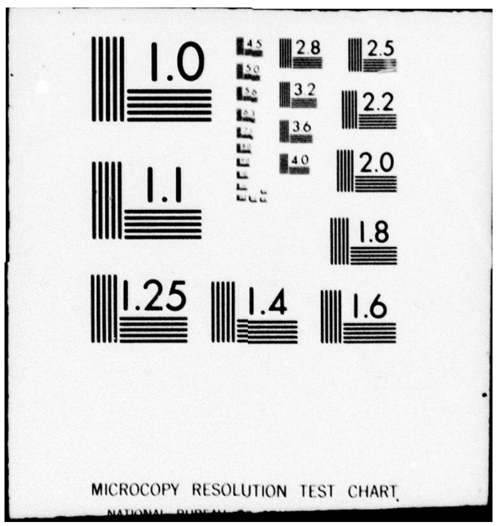
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THE INTEGRATION OF SHIP ELECTRICAL SERVICE POWER WITH SHIP ELECTRICAL PROPULSION POWER

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ABSTRACT

Three basic systems are examined on a conceptual qualitative basis. Relative advantages and disadvantages are discussed. The latest development progress of the component parts are delineated and the prospects for successful development are projected. A baseline for comparison on the basis of cost acquisition, maintenance and manning, fuel costs, tactical capability and projected reliability will be the SPRUANCE class destroyers with their present propulsion system replaced by an electrical system.

THE INTEGRATION OF SHIP ELECTRICAL SERVICE POWER WITH SHIP ELECTRICAL PROPULSION POWER

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The subject of this paper may strike some readers as being optimistically unrealistic. The thought will occur to them that the integration of ship electrical power propulsion systems with the electrical power ship service systems might be accomplished provided first acceptable ship electrical power propulsion systems existed. Now it is true that several naval vessels currently use electrical power for propulsion. The question is "Are these operational electrical propulsion systems now suitable for integration with the electrical ship service power?"

The first large application of ship electrical power was Jupiter built in 1911 having 4100 KVA, wound rotor (for speed control) induction motors. Later five battleships were powered by a.c. drives of over 22,000 KVA. The largest ship electric drives were installed on the carriers USS SARATOGA and USS LEXINGTON in the nineteen twenties. The total installed power of each ship was 176,000 HP applied to four screws of 44,000 horsepower per shaft.

Previously the submarine, by necessity, was powered by an electric motor supplied by batteries when running submerged. Diesel generator sets were used to charge the batteries between dives and the submarine had to be at the surface or at snorkelling depth when doing so. These submarines had d.c. motors of approximately 5,000 HP. At the surface, combined diesel generator and battery sources would deliver maximum power to the propulsion d.c. motor. Motor generator sets were used to provide the a.c. ship service electrical power, with the d.c. motor either on the battery or the diesel generator. These submarines, in a sense, had the first integrated electrical power systems as the primary source of electrical energy (the battery or the generator) was used by both systems. To the extent that this can be considered an integrated system the answer to the previous question would be yes.

Propulsion d.c. motors, both superconducting and normal conducting of a new type, are under development by the Navy. Delivery of 3,000 HP hardware will begin in April of this year. These propulsion systems at the 40,000 HP level could be combined with the ship electric service system by using a large motor generator set (around 3,000 KW) to supply the a.c. ship power required. This would probably be, however, not an acceptable solution as the acquisitional, maintenance and repair costs could be considered excessive, not to mention the weight and size of the units compared to separate prime mover generator sets.

It was stated above that the Navy now has under development new type d.c. machines; but there is also a third type, the permanent magnet a.c. motor, which is just beginning to be considered. The reason for all this development is that the advantages claimed for the electrical propulsion system have proven to be too costly, and too heavy for further consideration at present. The advantages of electrical propulsion are very attractive, among which advantages are:

a. The location of prime movers can be taken to reduce the amount of expensive "real estate" used by the gas turbine ducts, gas turbine engines can more readily be replaced.

b. Long runs of shafts can be reduced.

c. All reduction gear boxes, ancillaries and the associated accoustic signature can be eliminated.

d. The propulsion power transmission system allows a variable speed ratio between the prime movers and the propeller which increases the efficiency of the prime movers.

e. A fixed pitch propeller (more efficient and reliable than the controllable pitch propeller) can be used.

f. The total power plant (for ships with more than one shaft) can be used in any desired configuration in order to operate all shafts with minimum fuel usage and/or maximum engine life for any power level desired. This is a considerable savings.

g. Failure of a gas or steam turbine only reduces the total power available; the propulsion power transmission system allows the remaining available power to be equally distributed between all propellers.

h. Ship designs involving odd numbers of installed gas or steam turbines are practical.

The present Navy electrical propulsion machinery development has as its objective the attainment of the above advantages while at the same time remaining as cost effective and as weight advantageous as the gas or steam turbine, reduction gear box, its ancillaries, present shafting, gas turbine ducting and the controllable reversible propeller (CRP).

While the development may not attain all of its objectives, it is considered at the present time to be able to approach close enough to these objectives that the advantages will greatly outweigh the small difference from parity with the present mechanical propulsion systems.

Because d.c. motors of large power, at the kilohorsepower level and higher, cannot be operated at the gas turbine output speeds used to power ship service a.c. generators the use of the motor generator set for ship service power now will be too large and heavy to offer attractive advantages. There are however, other alternatives which can combine with the ship electrical propulsion power systems to provide ship service electrical power. It is these alternatives which will now be examined. The SPRUANCE class destroyers will be used as a baseline. Figure 1 shows the present propulsion system and present electrical service system arrangements.

The present Navy electrical propulsion machinery development program will produce d.c. motors of some form, superconducting or normal conducting novel type. The generators which are used to power the motors can either be of the d.c. superconducting, d.c. normal conducting, or a.c. normal conducting type, the latter normal conducting a.c. generators would have a rectified output. Consider the superconducting d.c. generator or the d.c. normal conducting generator first. To provide a.c. power from these type generators will require an inverter of approximately 3,000 KVA capable of operating over a two to one voltage range, say 500 to 250 volts. The reversing or crash back maneuver however, may make this alternative unacceptable because, at some point in the maneuver the d.c. bus voltage gets considerably below the 250 volts. Consequently there would be no available ship service power coming from the inverter at that time. The situation can be overcome by using a large braking resistor on the d.c. motor bus and controlled rectifiers between the d.c. generator and the motor. The deceleration of the ship may not be as rapid as would have occurred with the electrical propulsion system separate from the ship service electrical system.

The second alternative is to use the a.c. generator rectified at fixed speed (to maintain 60 Hz) and relatively fixed excitation (to maintain a suitable voltage range on the a.c. bus). The rectifiers would be controlled rectifiers to vary the d.c. bus terminal voltage to the d.c. electrical propulsion motor thus controlling its speed. This alternative can provide for the crash back maneuver. The harmonics reflected on the a.c. bus as the speed is varied and the controlled rectifiers chop the d.c. current can become objectionable, finally making this alternative also unacceptable. This is the generic type of system proposed for consideration as a candidate system for the T-ARC. With present a.c. generators available, the use of wye-delta buffer transformers can reduce the severity of the harmonic reflection problem on the a.c. bus but never eliminate it. At best it may finally prove to be unsuitable for this ship. In passing, there are commercial ships and ships of foreign powers which have just such systems installed today.

The a.c. generator being developed by the Navy is quite different electrically than any now in use by the Navy or the public utilities. It has five three phase groups of windings equally electrically spaced from each other and each group has four parallel windings. Five separate d.c. buses are formed from three phase full wave rectifier bridges (six rectifiers per parallel winding, twenty four rectifiers total for one d.c. bus) per group. The five d.c. buses are then tied in parallel by means of interphase, or better perhaps, intergroup transformers which considerably reduce the harmonic content of the currents flowing in the generator phases.

This Navy electrical propulsion hardware development is all at the 3,000 HP level. The laboratory performance of the motors and generators when assembled into a twin shaft system will enable the Navy to select the best overall system for projection to the 40,000 HP level. The baseline ship with electrical propulsion and separate ship service systems is shown in Figure 2. The author suggests that the selection of the electrical propulsion system be based not only on the performance of the electrical propulsion system alone but also on its potential as a candidate for integration with the ship service electrical system. In that event, the author believes the a.c. generator electrical propulsion system will prove more adaptable for total electrical power integration.

The laboratory assessment of the electrical power integration potential of the a.c. generator can be done at the 3,000 HP level without disturbing the present development. The present a.c. generator can be utilized later (after its intended evaluation) as a dual winding generator to provide both a.c. and controllable d.c. power from separate windings in this a.c. generator. The present rectifiers would have to be replaced with controllable rectifiers and the a.c. generator operated at constant speed. One of the three phase groups and its associated rectifiers would be removed from the d.c. bus. Subsequent to which, these rectifiers would be then removed from that three phase group. That three phase group would then supply the a.c. bus. This is not quite as good as designing a dual winding a.c.-d.c. generator but it would be sufficient to demonstrate that the harmonic reflection, due to varying the d.c. bus terminal voltage by controlled rectifier action at fixed generator speed and field current, on the a.c. bus would be greatly reduced and consequently acceptable compared to the second alternative described above.

The present answer to the question above would be that there are now no suitable operational electrical propulsion systems that can be integrated with the electrical ship service systems with advantage, primarily because the requisite components are nonexistant. The Navy development program has, however, margin to bring into being the requisite components. Even accepting this as being so the question will arise just what are the advantages in integrating the two systems? If one assumes a 3,600 KVA nominal ship service load (including growth) and if one assumes that the maximum load now of 3600 KVA occurs under battle conditions when presumably the ship would be operated at full speed then each generator would need to have a capacity of 15 MW (20,000 HP) plus

900 KVA or a total of 15,900 MW, an increase of 6% over the present projected capacity. The turbine would have to provide 20,000 HP plus 1,200 HP or 21,200 HP. This is within the capacity of the LM 2500 gas turbine without change.

The first advantage that accrues is the removal of three ship electrical service gas turbines with their reduction gears, ancillaries and the ducting plus the associated ship service a.c. generators. This is a considerable reduction in acquisitional, operational and maintenance costs. Further, by doing that it is entirely possible that a more frequency stable a.c. system, possibly going from Type I to Type III electrical power for the entire ship service electrical power will be acquired. A qualitive argument runs that the speed stability of a large engine is better than that of a small engine. The cost of increasing the electrical power of the projected electrical propulsion generator by 6% should be considerably less than the cost of three gas turbines, gear boxes, ancillaries, ducting, and the a.c. generators. In addition, all this elimination should bring about a considerable reduction in the airborne acoustic pollution. A consequent increase in reliability will just be mentioned.

There is another advantage which accrues and it may be the more important one. The fuel economy of the combined electrical plant will be better than the fuel economy of the two separate electrical plants. That is because the specific fuel consumption (SFC in pounds per horsepower hour) of the LM 2500 gas turbine is (at full rated output - 3600 rpm) 0.4038. That of the ship service gas turbine (Allison 501-K17) is .679 at rated output, 2,150 HP. At lighter ship service loads the gain in SFC would be still appreciable because the overall relative change in load for the LM 2500 would not be as great as that for the Al501-K17.

Suppose one looks at the half speed cruise condition where only 1/8 of the total available electrical propulsion power is required due to the "cubic propeller law." One LM 2500 and one generator would be used to power both propeller motors. Thus each motor would require 5,000 HP and the generator would be delivering 7,500 KW of electrical power or 1/2 of its rated capacity. Adding the 3,600 KW of ship service electrical load to this generator would require 11,100 KW from the generator or 14,800 HP from the turbine. At 3,600 rpm and this power requirement the LM 2500 would have an SFC of 0.425. If the electrical system were two separate systems the overall SFC of the LM 2500 at 7,500 KW and two Al501-17K gas turbines at 1,800 KW would be

$$\frac{7500 \times .527 + 2 \times 1800 \times .679}{11,110} = .576 \text{ pounds of fuel per horsepower hour.}$$

This is not as good a gain as that at full power but in a typical mission approximately 3/4 of the time may be spent in such a cruise mode. For a total of 3,000 hours with 3/4 of that elapsed time in such a mode a net reduction in fuel consumption of

$$(.576 - .4425) \times 11{,}100 \times 3{,}000 \times \frac{4}{3} \times \frac{3}{4} = 4.496 \times 10^6$$

pounds of fuel would be obtained.

This is just the fuel savings due to the combined integrated electrical system over the split electrical plant (Figure 3 compared to Figure 2). If the two screws of the ship are mechanically powered, each LM 2500 engine would deliver 5000 HP (Figure 1). The ship service electrical system is now alone. The specific fuel consumption at 1800 RPM for the LM 2500 is .661. That of the two Al 501-17K engines at 1800 KW is .701. The overall SFC of the ship mechanical-electrical system is

$$\frac{(2 \times 5000 \times .661) + (2 \times 2400 \times .701)}{14{,}800} = .665 \text{ pounds of fuel per horsepower hour.}$$

The total fuel savings at cruise for the combined integrated electrical plant ship (Figure 3) compared to the mechanical-electrical ship service ship (Figure 1) is

$$(.665 - .4425) \times (10{,}000 + 4800) \times \frac{3}{4} \times 3000$$

$= 7.409 \times 10^6$ lbs of fuel. At 330 lbs of fuel per barrel and at $12 a barrel the dollar savings is $269,400 per ship.

This gain in fuel economy now reveals a significant fact. The reduction in fuel consumption is greater for the combined electrical plant (4.496×10^6) than just the gain acquired by using electrical propulsion, claims d and f above, $(7.409 - 4.496) \times 10^6$ or 2.913×10^6 lbs of fuel compared to the mechanical propulsion-electrical ship service baseline ship. Consequently, if claims d and f are cogent arguments for electrical propulsion on SPRUANCE class destroyers than what has just been calculated is an even more cogent argument for an integrated electrical plant aboard the same class. The statement will apply to all ship types where the SFC of the electrical ship service power prime mover is greater than the SFC of the propulsion power primer mover and the propulsion power transmission link between that prime mover and the propeller is an electrical one, having suitable potential for integration with the electrical ship service power.

Other questions still remain to be answered. How does one start the LM 2500 engines? If shore power is available, the generator (designed to have a squirrel cage amortisseur winding and using reduced voltage starting controls) can be used as an induction motor to start the engine or an onboard start can be provided by an APU which can be further used to supply bleed air.

After one engine is started the power from that generator can be used to start the other engines. One could investigate the efficacy of operating with spinning reserve as the public power companies do. One engine can be used to power the ship and spin another engine or two by means of the latter engine coupled generator acting as a synchronous motor. Then when desired at any time one could immediately go (limited by throttle fuel rate change) to 1/2 or 3/4 propulsion power by throttle advance upon command. At full power with all engines running and the a.c. generators locked in synchronism on a paralleling a.c. bus, maximum frequency stability for the 60 Hz system would be achieved.

The magnitude of all voltage transients caused by pulsed loads upon the 60 Hz ac bus would be minimized and it would be less than that now caused upon the ship service generators. Two LM 2500 engines operating at cruise speed of 80% max speed would provide the electrical system basis for the AEGIS weapon system with better voltage stability than can now be provided by the planned ship service generators plus converters.

Another question of vulnerability arises. With three ship service turbines and generators, a hit on any one of these will still leave the requisite two sets in service. In the integrated electrical plant ship such a hit would miss because the ship electrical service generator and/or turbine would not be there. On the other hand, suppose a propulsion prime mover and/or its generator were hit. In the separate electrical plant ship, the ship service electrical power capacity would be intact and the top speed of the ship would be reduced to 91% of max speed obtainable with four engines. In the combined integrated electrical plant ship one could keep the ship service electrical capacity intact if one were willing to settle for 89% of maximum speed. The cruise speed would of course be unaffected. Thus on a vulnerability basis the integrated electrical plant should be at least equal to that of the two separate electrical plants.

To recapitulate the advantages of the integrated electrical plant are:

(1) Greater fuel economy by a factor of two than can be gained as claimed for an electrical propulsion system compared to a mechanical propulsion system.

(2) Considerable reduction in acquisitional, operational and maintenance costs with a corresponding increase in reliability.

(3) Better ship service electrical power due to greater frequency stability and greater voltage stability with less transient voltage (due to pulsed loads) disturbances.

(4) Decreased acoustic signatures.

(5) More volume will be available for weapons space assignment.

(6) Reduction in manning requirements.

Not included in the above, are the additional advantages listed in the claims for an electrical propulsion system compared to a mechanical propulsion system. Those listed directly above are the potential gains which could be acquired by combining or integrating all the electrical power aboard the baseline ship.

That is not to say there will be no problems when (hopefully) such an integration is finally attempted. But they are problems of an engineering nature well within the present capability of the state-of-the-art to solve.

PRESENT ARRANGEMENTS

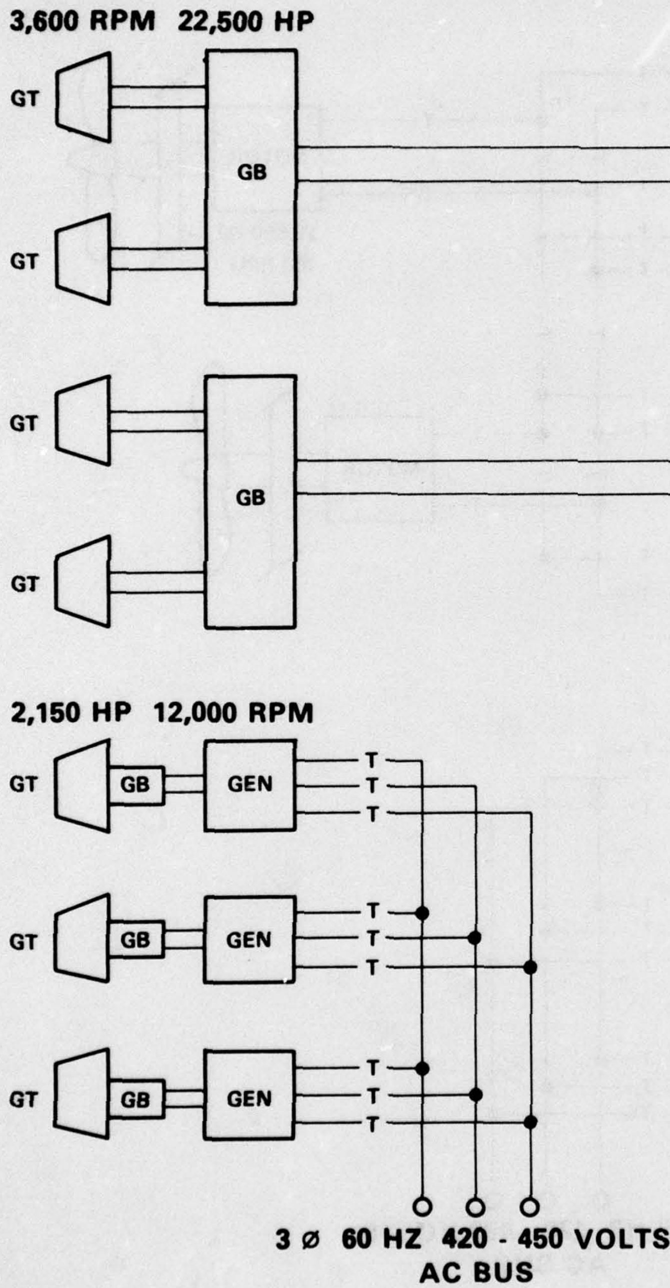

FIG 1

FUTURE PROJECTED ARRANGEMENTS

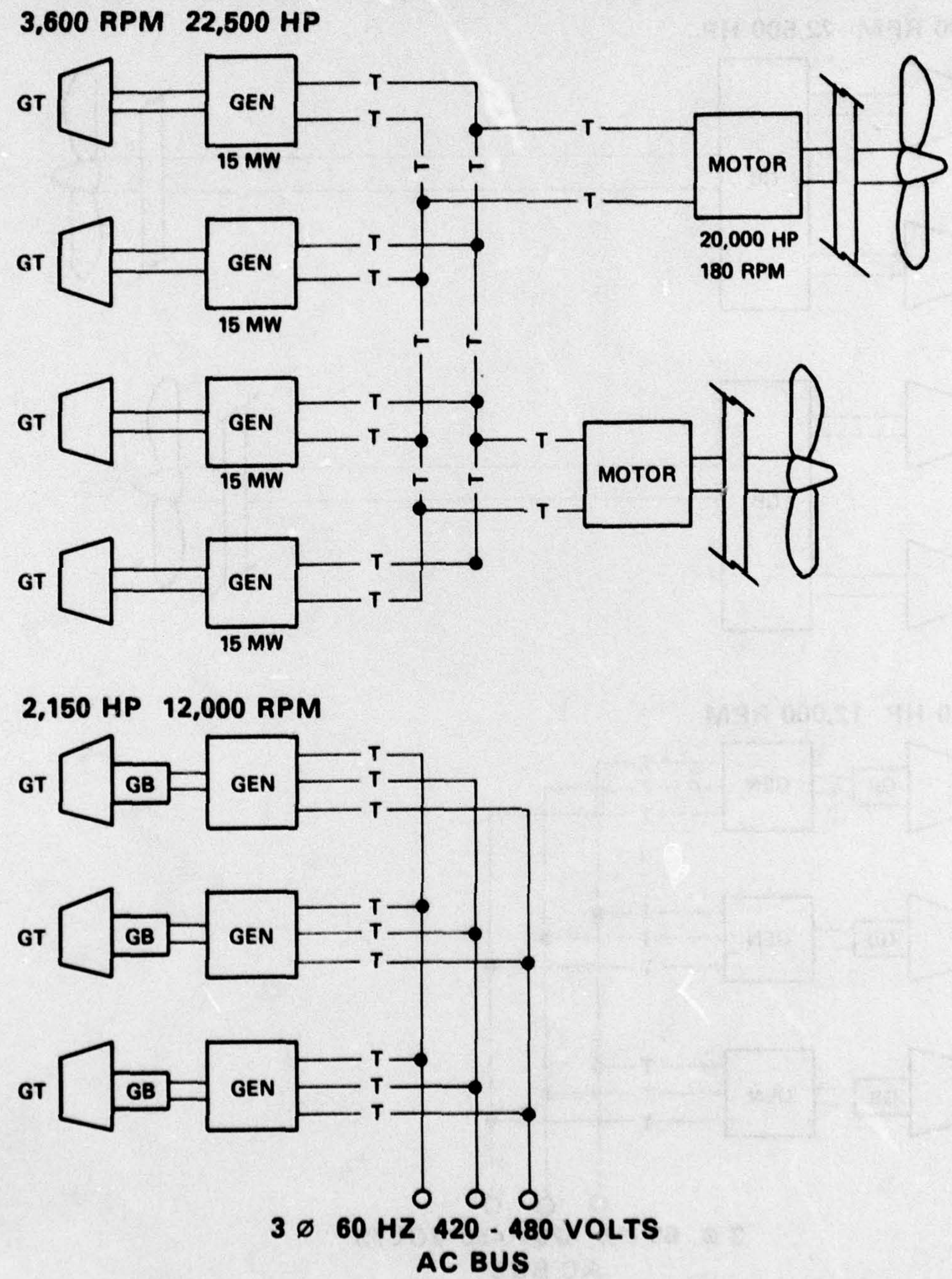

FIG 2

PROPOSED FUTURE ARRANGEMENTS

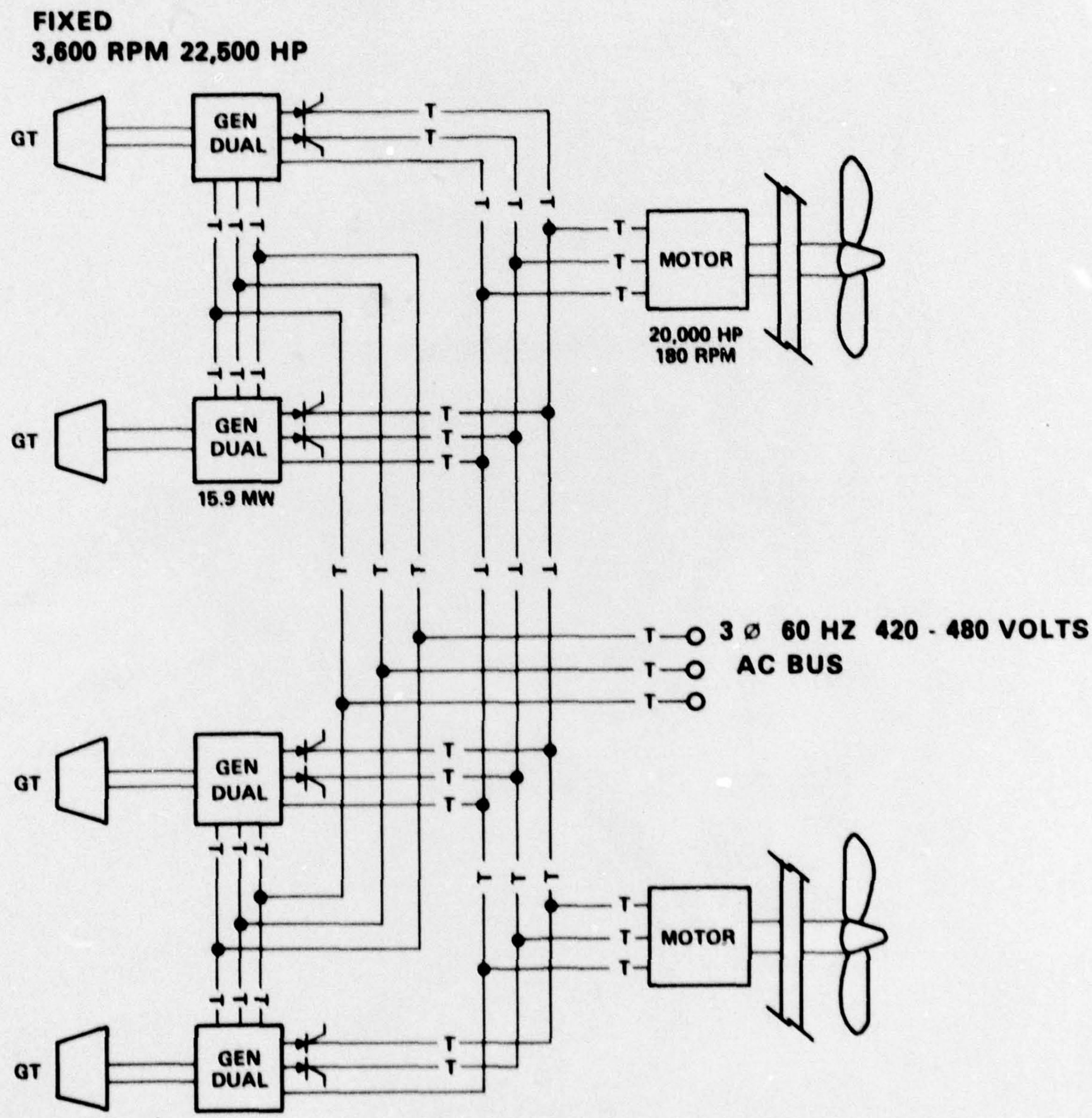

FIG 3