SHAFT-DRIVEN GENERATORS

BY

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Synopsis

The article begins by reviewing the reasons for the increase in popularity of main-engine-driven auxiliary generator systems and goes on to describe the methods in general use. No system can be regarded as a direct replacement for independently-driven generators and the various compromises in respect of quality of supply, performance, reliability and protection are examined. A review of operational experience follows and the article concludes with a discussion of probable developments over the next ten years.

Introduction

This article is based on information collected for a study carried out for the Ministry of Defence. Much of the information presented applies to both merchant and naval vessels.

The present policy of using gas turbine propulsion in naval ships rather than steam, has enforced a change in generator prime mover policy from a mixture of steam and diesel to all diesel. The MOD have been aware for some time that a number of merchant vessels were being fitted with generators which used the main propulsion engines as their source of power. They were particularly interested in the type of shaft generator system which employed inverters, as used in several commercial applications, and it was thought that there were a number of potential advantages, mostly arising from the fact that diesel generators would not be run at sea. Briefly these were:

(*a*) Reduction in diesel maintenance costs
(*b*) Increase in prime mover reliability
(*c*) Possible small weight savings
(*d*) Reduction in radiated underwater noise.

It should be explained that warship generating equipment does, in general, have to meet more stringent requirements than normal marine equipment. These include voltage and frequency response, short-circuit performance, limits on the harmonic content of the waveform supplied to users, limits on both conductor-borne and radiated interference. Another major requirement is the ability to withstand significant shock levels. Availability of electrical supplies is of paramount importance in a warship and is to a large extent dependent on the reliability of the prime mover. Warship designers are presently under great pressure to reduce costs, so that cost is an important factor when considering new equipment.

As regards the inverter type system, one of the problems for a warship application is that the inverter output is incompatible with usual warship electrical performance standards, particularly with respect to harmonic content and interference. A trial was therefore carried out on a vessel fitted with this type of system which showed that, although the system was outside warship tolerances in certain aspects, the differences were not as great as had been supposed. It was therefore decided that a study should be carried out, with the aim of establishing the feasibility of using shaft-driven generating equipment employing inverters. If it could be shown that this equipment had substantial advantages compared with the usual diesel generator installations, then it would merit consideration for future ships. Though a specific system was selected for the study, this article also gives some information on other methods used to provide an acceptable electrical supply from a generator driven by the main propulsion unit.

The General Problem

In all shaft-driven generator installations, the general problem to be overcome is the reconciliation of conflicting requirements, namely: those of the ship's electrical equipment which demands constant voltage and—in the case of a.c. systems—constant frequency, and those of ship operating patterns, which demand variation in prime-mover speed dependent upon the ship speed and the sea state.

First Installation

In early applications, where d.c. auxiliaries were used, a generator of a few kilowatts was driven from the main shaft by belts or chains or through an auxiliary drive pinion in the main gearbox. As long as the shaft speed was within the designed operating range of the generator, the automatic voltage regulator was able to maintain the voltage sensibly constant.

As ship size grew, there was a gradual change to a.c. installations, and methods were sought to obtain constant frequency. The first a.c. installations limited the use of the shaft generator to a narrow range of shaft speed so that the system frequency was maintained within acceptable limits; outside this range, the diesel-driven auxiliary generators were used.

Though this was reasonable for ships which spent most of their time at a constant speed, it severely limited the usefulness of the concept. To overcome this obstacle, a number of solutions were considered and these are dealt with later. Firstly, the incentives that led to their development are detailed.

Development Incentives

It is worth reminding ourselves what the advantages of shaft generators were considered to be, as it is these which forced the pace of development. If the main engine could be used to obtain auxiliary power, then the advantages envisaged were:

(*a*) Savings in fuel costs, because fuel for main diesel engines in merchant ships is cheaper than that for diesel generators.
(*b*) Savings in maintenance and repair costs, because of the reduction in running hours of the diesel auxiliary sets.
(*c*) Savings in lubricating oil costs for the same reason as (*b*).
(*d*) A possible reduction in the number and rating of the auxiliary diesel generator sets, depending on the duty for which they had to be designed.
(*e*) Consequent reductions in space, weight and through-life cost resulting from the above factors.

Choice of Drive

The drive for the shaft generator may be by one of the following methods:

(*a*) Belt or chain drive from the propeller shaft
(*b*) Direct coupling into the propeller shaft line
(*c*) A power take-off from the main gearbox
(*d*) Coupling to the free end of the main engine.

Each method has its advantages, and ship owners have their preferences for one or the other of them. Method (*b*) is limited by the maximum diameter of the stator that can be accommodated and the number of poles that can be fitted on the minimum diameter shaft to give a reasonable machine design for the rating required. Typical shaft speeds for this arrangement are about 80 to 120 rev/min.

Method (*c*) offers the opportunity to choose the optimum design of alternator by selecting the gear ratio, as the output frequency of the alternator is not limited to normal supply system frequencies. The method has the disadvantage that either a separate gearbox is required or an additional pinion—and sometimes a clutch—must be added to the main gearbox. It may therefore impose constraints on the plant layout, particularly if the after end of the ship is very fine. Typical generator speeds may range from 1000 to approximately 3000 rev/min. Above this latter speed it may be necessary to change the type of rotor construction to that used in units driven by high-speed turbines; this would considerably increase the cost and hence offset some of the advantages.

Method (*d*) is preferred by some owners as it may eliminate the need for a gearbox or for an additional pinion in the main gearbox. It is a convenient method for use with medium-speed diesels, but it may entail a longer engine room. It has recently been proposed that a similar method be employed where the prime mover is the compressor of a gas turbine. This scheme offers the advantage of a reduction in the speed range over which the generator will have to operate compared with that of the main shaft, due to the smaller variation in speed of the compressor compared to the power turbine shaft.

Where the method of drive adopted is a power take-off, either from the gearbox or from the free end of the engine, then a number of limitations may be imposed on the various solutions proposed hereafter.

General Solutions

It can be seen from the foregoing that there were good reasons for pressing ahead with development. A number of schemes to obtain constant frequency have been proposed, and most of them have been fitted to ships in service. The methods presently available are:

(*a*) d.c. shaft generator—d.c./a.c. motor alternator set.
(*b*) a.c. shaft generator—rectifier—d.c./a.c. motor alternator set.
(*c*) a.c. shaft generator—rectifier—static inverter system.
(*d*) shaft-driven induction generator and motor alternator set.

Other methods which could be used (but which, as far as the authors are aware, have neither been developed to the same extent nor have they been fitted in ships) include:

(*a*) A variable-speed input/constant-speed output epicyclic gearbox driving an alternator.

(*b*) A hydraulic drive comprising a variable-speed pump and a constant-speed motor driving an alternator.

D.C. Shaft Generator—D.C./A.C. Motor Alternator System

The a.c. system frequency is controlled by the speed of the motor alternator set, and a suitable synchronous speed must therefore be chosen. It is doubtful whether this system would be practical for outputs much above 750 kW or for speeds above 900 rev/min because the machines would be very large. The overall efficiency of this scheme is about 65 to 75 per cent.

A.C. Shaft Generator—Rectifier—D.C./A.C. Motor Alternator Set

This scheme takes advantage of the greater kW per rev/min available from an a.c. machine. If necessary, the rectifier output can be shared between two d.c./a.c. motor alternator sets. This system has not been evaluated by the authors, but it has been considered recently by one company who required approximately 1 MW of auxiliary power, and who found it to be competitive with other shaft alternator systems. The limitation of both this and the d.c. scheme becomes one of space and reliability required by the increased number of rotating machines to be accommodated and maintained. The overall efficiency will be slightly higher than that of the d.c. scheme because of the higher efficiency of the a.c. machine.

A.C. Shaft Generator—Rectifier—Static Inverter

This system has been developed extensively by two manufacturers in Europe and has been fitted into some forty or more ships during the last seven years. The limitations of this scheme tend to be those imposed by high-power electronics and by the size of the equipment (which includes a synchronous compensator, chokes and capacitors) compared with a diesel generator set of similar rating. Installations have been supplied rated at about or in excess of 1 MW per shaft. Until recently, most of these installations were fitted by continental owners but, in 1971, Seatrain Liners fitted two 1-MW units in their gas-turbine-driven *Euroliner;* this has since been followed by a further three ships' sets. The overall efficiency of this scheme is about 85 per cent.

Induction Generator

This system, too, has been developed in Europe, but it has not found the same degree of acceptance as the previous system. The frequency is controlled by the speed of a motor alternator set which derives its power from the rotor circuit of the induction generator. The motor alternator also provides the excitation for the induction generator and the reactive power demands for the generator and its loads. Again, this system has not been evaluated by the authors, but others have commented that, for the larger outputs, a very large motor alternator set would be required because of the amount of reactive power to be supplied—though this can be alleviated to some extent by installing power-factor-correction capacitors. Typical overall efficiencies are in the range 80 to 82 per cent. There are a number of variations of this scheme, including one in which the rotor energy of the shaft generator is dissipated in a resistor to provide heat for hot-water systems or low-grade steam to drive a small turbo generator; in the latter case a separate source of excitation is required. Typical overall efficiencies are in the range 69 per cent. at maximum shaft speed to 89 per cent. at 80 per cent. shaft speed; the inclusion of the turbine generator will increase the operating efficiency to about 90 per cent.

Effect of Type of Propeller

All of the above systems may be used in ships with fixed-pitched propellers. However, for a given output, generator size increases with the range of shaft speed over which it has to operate and this could prove a limiting feature, except in ships which spend most of their sea time at an almost constant speed. The generator is usually designed to give its rated output over the top 25 per cent. of the shaft speed range with a progressive reduction down to 50 per cent. at 50 per cent. shaft speed. Below this, the shaft generators would normally be shutdown in favour of the diesel alternators.

The inclusion of a controllable-pitch propeller (CPP) extends the range of ship operating conditions over which the shaft generator may be used. The inclusion of a d.c. link would enable the rough weather transients to be isolated from the a.c. system and allow a high degree of operational flexibility to be obtained. It may be possible to omit the d.c. link and use a synchronous generator if the shaft speed can be maintained sensibly constant over a wide range of operating conditions. The policy concerning controllable-pitch propellers varies from owner to owner. For example, the R.N. uses pitch control only for manoeuvring and slow-speed cruising; above this, variation of ship speed is obtained by varying the engine speed. This is done for a number of reasons, not the least of which is that it enables maximum economy to be obtained—bearing in mind that a warship spends over 50 per cent. of its sea time at speeds below 50 per cent. of the maximum. Its operational profile is quite different from that of a merchant ship. One company investigating the use of shaft-driven generators stated that, because of cavitation and erosion problems, they never use pitch control to vary ship speed below approximately 28 per cent. shaft speed—the reverse of the naval ship policy. It is concluded that, for a merchant ship, the CPP offers an opportunity to restrict the shaft-speed range over which the shaft generator has to operate and so keep its frame size—and hence its cost—to a minimum. However, in the case of naval ships with CPP, a considerable constraint is imposed on the design of the shaft generator as the shaft is still required to operate over a much wider range of speed than in a merchant ship.

Alternator: Static Inverter—Evaluation

A specific task undertaken was to evaluate warship application of the d.c. link static inverter scheme and assess likely developments over the next ten years. This article, although not detailing the findings, presents an impartial report of the investigations and highlights some of the problems found. Where possible, conclusions are reached upon the general application of shaft-driven generators.

Cost

Cost is dealt with first, as it is often the first aspect with which a shipowner or prospective purchaser is concerned.

Almost inevitably, the capital cost of a d.c. link static inverter scheme is greater than that of a diesel generator set of the same rating. A 1-MW system using continental equipment—at 1973 prices and excluding the cost of installation—costs about £105/kW compared with up to £80/kW for a British diesel generator. This is not unexpected, as the particular system studied included a

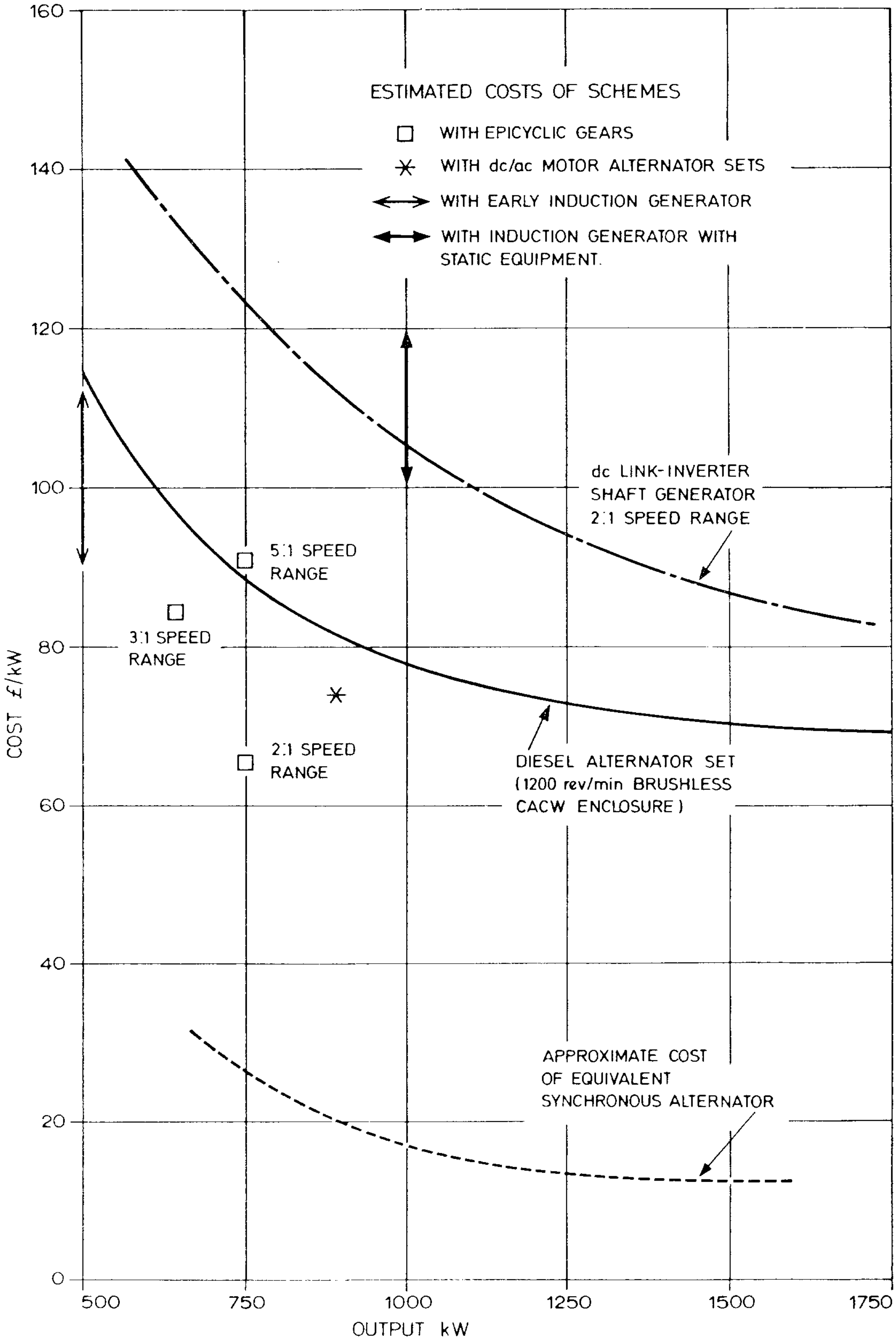

FIG. 1—COMPARISON OF FIRST COSTS OF ALTERNATOR INVERTER SHAFT GENERATORS AND DIESEL ALTERNATORS

number of additional components, i.e. a rectifier, an inverter, a synchronous compensator, capacitors and sometimes reactors and smoothing chokes to electrically isolate the variations in shaft speed from the constant frequency output to the a.c. system. When comparing cost, the comparison must take into account installation and running costs; these latter include maintenance and repair, lubricating oil and fuel. Reference (1) which deals extensively with this aspect shows that, provided the main engines use fuel which is approximately half the price of the fuel for the auxiliary diesel sets, the cost per kilowatt of power from shaft generators would be approximately half of that from diesel generators. Similar efficiencies were used for both the shaft alternator and the diesel alternators when performing the calculations; whereas, in practice, the overall efficiency of the shaft alternator system with a d.c. link will be some 10 to 12 per cent. lower depending on the system adopted and the designed operational speed range.

The annual cost depends upon the ratio of utilization of the shaft generator to the diesel-driven auxiliary generator sets. Compared with an all-diesel installation, the savings increase as more use is made of the shaft generator. They increase even more if fewer and smaller diesel sets can be fitted. However, it can also be shown that, when the price of fuel for the main engine is the same as that for the auxiliary sets, the saving on fuel is reduced to a few per cent. at best and any saving achieved will depend entirely upon other factors, such as the maintenance and repair costs for the diesel generators.

Reference (1) also shows that maintenance and repair costs are proportional to diesel running hours while, with fewer running hours, there will also be a reduction in lubricating oil costs. In shaft generator schemes, allowance was made neither for maintenance of the main engine nor for lubricating oil costs as they are considered to be present whether or not a shaft generator is fitted. No allowance was made for the cost of maintenance of the conversion equipment as, in the scheme investigated, none was fitted.

Various plant configurations based on gas turbine propulsion were also investigated and costed for the MOD. These showed that, in naval ships (where the same fuel is used for both the main and auxiliary engines), there was only a marginal difference in through-life costs between an all-diesel generator scheme and one with a shaft generator and fewer diesel generator sets. The figures did not, however, take account of repairs done at sea on diesels and therefore the difference between through-life costs is probably bigger than was estimated.

In general, it is concluded that a saving in cost is obtained only where there is a significant difference between the costs of fuel for the main engines and fuel for the auxiliary generator sets. The reduction in diesel maintenance, repairs, and lubricating oil costs also contribute to this saving. However, a deduction must be made for maintenance and repair of the additional (and more complex) electrical systems associated with any shaft generator system that includes a d.c. link.

In ships where a CPP and a constant-speed synchronous alternator may be used, a saving should be apparent even if the same fuel is used for the main and auxiliary engines. Thus it can be seen that the first three of the foreseen development incentives may be realized with certain plant fits but not with others. FIG. 1 compares the first cost of alternator inverter shaft generators with that of diesel alternators.

Space

The next aspect to be considered is the space occupied by the plant. In a d.c. link static inverter scheme, there are inevitably more items to be accommodated than in a diesel generator scheme; in addition to the shaft generator, there is a rectifier, inverter, synchronous compensator and the control equipment. In some instances, it may be possible to reduce the space occupied by mounting the rectifier in the cooling air stream of the shaft generator. If a water-cooled generator is used, then it becomes difficult to do this by the very nature of the machine design and enclosure.

In early plants, space was saved by using the auxiliary generators in a dual role and declutching the diesels so that the generators could then be used as synchronous compensators; as this led to a compromise in machine design and to difficulties with clutches, a separate compensator, started by a pony motor, is now fitted as standard. Even though it may be possible to dispense with a diesel alternator, no advantage is gained because the space vacated is taken up by the compensator. Space has to be found for the static equipment which, for a 1 MW output, would occupy a volume of approximately 10 m^3 (5 m long $\times$ 0·8 m deep $\times$ 2·5 m high).

Although it may be possible to provide this space in the engine room in a merchant ship, in a naval vessel it would be difficult and space would have to be found eleswhere. This may be an advantage. Under certain operating conditions, the machinery space temperature can rise to well above the normal ambient; if the static equipment had to be designed to meet this requirement then considerable additional cooling would be required, further increasing the bulk of the equipment. The capacitors in particular become unstable at high temperatures.

It is concluded that, in general, the space demanded by a d.c. link scheme with diesel generators is greater than that required for an all-diesel scheme. This may be acceptable in a merchant vessel but is likely to be embarrassing in a warship. The same conclusion is also true concerning weight.

Performance

The performance of a shaft generator system may be discussed under a number of specific headings, namely:

(*a*) *Quality of Supply*

The most noticeable feature of the waveform produced by a static inverter is the presence of commutation notches caused by commutation of the thyristors. This phenomenon is dealt with in reference (2). To eliminate these completely would require very large filters and, in a commercial application, it is not considered economic to do so. The authors know of only one report which shows the interference to be detrimental to equipment operation in merchant ships. In naval ships, however, the supply has to be of a much higher standard to enable the sophisticated electronic equipment to meet its specified duty. Thus additional filters would be required either at the inverter output or, more sensibly, at those equipments which require a pure supply. There is, of course, an alternative method and that is to provide motor generator sets to give the pure supplies as necessary: however, this is considered a retrograde step as, at present, the Navy is looking into ways of reducing converted supplies required in its ships.

The harmonic content of the supply in a warship generally has to comply with the requirement that any individual harmonic should not exceed 3 per cent. and the total harmonic content should not exceed 5 per cent. of the fundamental. Limited trials in merchant ships have shown that these criteria can be met with shaft-driven generator systems.

(*b*) *Voltage and Frequency Response*

Voltage and frequency response are governed by a number of factors, including the type of excitation used. A fast voltage response is obtained by using static excitation on both the shaft generator and the synchronous compensator, and the extent to which it is required depends upon the ability of the synchronous compensator and its AVR to meet the transient loads. If brushless excitation is used for the compensator rather than static excitation, then the voltage transient may not meet the naval requirements. The frequency response is a function of the time constants of the shaft generator, its AVR, the inertia of the synchronous compensator and its ability to return to the normal frequency after a transient. Both the voltage and the frequency response meet the requirements laid down by the Classification Societies. Typical responses to transients are shown in Ref. (2).

(*c*) *Short-Circuit Performance*

The short-circuit performance of an alternator static inverter system differs from that of a diesel generator. Under short-circuit, the output of the inverter is either limited or switched off for the duration of the fault, and the fault energy is provided by the synchronous compensator which—because it has no prime mover—will slow down. Normally the compensator is designed to provide sufficient energy to rupture the largest downstream fuse and provide discrimination throughout the protection chain. By its very nature, the system cannot operate the same way as a conventional diesel-driven synchronous generator in response to high impedance faults (neither is it capable of giving a sustained output under short-circuit conditions) and the correct choice of protective relays is important to ensure correct discrimination.

(*d*) *Parallel Operation*

In d.c. link static inverter schemes, there appears to be no difficulty in operating in parallel with a diesel generator, provided that the appropriate functions are built into the control system. It is common practice to run diesel-generator sets in parallel with shaft-generator systems, either during the start-up or shut-down of the latter. In simple systems which use a CPP and a synchronous machine, problems may occur because of the different sizes—and hence the different characteristics—of the two prime movers; however, these can be overcome by correct design of the control systems.

(*e*) *Radio Interference*

In discussions with commercial shipowners, only one instance was encountered where radio interference was a problem and it was solved by changing the radio receiver affected. However, over a small frequency range, the level of broad-band interference at the inverter terminal is generally above that specified by the MOD and therefore it could affect the performance of some naval equipments.

Reliability

It is difficult to quantify the reliability of the particular scheme studied as not all faults are reported. However, the impression gained from discussions with manufacturers and shipowners was that most of the faults occurred in the control system and associated components. This was confirmed by analysis—faults in these areas accounted for approximately half of all those reported.

It was also deduced that the overall reliability of the system studied was likely to be higher than that of a diesel alternator set, but no comparable quantitative data were available to substantiate this. What did come to light though was the occurrence of a number of 'mystery' faults which had required the attention of the manufacturer's own engineers because diagnosis had been beyond the capability of ship's staff.

Development Over the Next Ten Years

Future development, particularly in the field of power electronics, should reduce the initial cost of the power electronics and their controls. It may also mean that the line-commutated inverter presently used will be replaced by a self-commutated unit; at present, the cost of such a device at the ratings considered is prohibitive. It may also be that, during the next ten years, variable-ratio epicyclic gears and hydraulic drives become more favoured where the shaft generator is required to operate over a wide range of speeds. Where full use of a CPP can be made, advantage will be taken of this to eliminate the conversion equipment, and constant-speed synchronous machines will continue to be installed.

Discussion of Advantages and Disadvantages

Generally, the benefit of the advantages for merchant ship application foreseen before development of the d.c. link inverter scheme have been realized, but space and weight are increased. A bonus appeared in the form of a reduction in noise levels in the engine rooms because it was no longer necessary to run the diesel generators.

Naturally, the advantages had been gained at some cost. For example, use of the main engine to produce auxiliary power, although it cuts down the need to store and use high-cost fuel, leads to reduced shaft power and ship speed when the shaft-driven generator is in operation. The reduction in speed can be as much as 2 knots at approaching full output and, consequently, for the same ship operating profile, fuel consumption is increased and endurance is reduced. In order to give a specific performance, it may be necessary in certain cases to fit a larger engine in a given hull size, and this could outweigh the advantage of a shaft generator system.

Other potential disadvantages include the additional space which may be necessary, depending upon the scheme chosen, and the occurrence of faults that are beyond the capability of ship's staff to repair.

Conclusion

Generally, merchant shipowners have been justified in fitting generators which derive their power from the main engines. For naval ships fitted with inverter type systems, there is no significant saving in size or weight even under the most favourable circumstances. It is difficult to be precise about the reliability because of the present lack of data but it would appear that there should be a reliability advantage compared with diesel generators. There may be a small advantage in through-life costs but this must be weighed against the fact that development costs would be incurred in making existing designs conform to present MOD electrical performance standards. The MOD are conducting a survey of the other types of shaft generator system; if any of these look favourable, a more detailed study may be initiated.

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