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TRANSACTIONS (TM)

DESIGN OF ELECTRICAL SYSTEMS FOR WARSHIPS

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Read at 1730 on Monday 28 March 1983

ISSN 0309-3948
Trans I Mar E (TM)
Vol. 95, 1983, Paper 43

Design of Electrical Systems for Warships

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SYNOPSIS

Modern warships have become highly complex and are full of densely packaged systems and equipments which must be integrated into the overall ship design. The electrical main supply and distribution system—the common artery on which all of the ship's systems depend—must be designed so that it is capable of providing continuity of power, at a defined quality, to all services under various operational conditions, including that of action damage. The author discusses the considerations involved in the design of systems for generation, distribution and control of the main supply system to ensure continuity of supply. Methods for determining the connected loads, to enable the generator to be selected at an early stage in the design, are discussed. The power supply and distribution arrangements are identified, together with protection of the systems and quality of the power supply. Other dependent electrical systems are also mentioned. The author identifies the problems that make RN warships different from commercial marine ships, particularly those of environmental and operational conditions, and concludes by giving a view on future ways to improve the operation and reliability of electrical power and distribution systems.

INTRODUCTION

A modern warship is a complex package of propulsion, weapons, communications and surveillance equipment, and of course accommodation, aimed at achievement of the vessel's operational role in times of both peace and war. Ship design is of necessity a technical compromise, between the disciplines of hull, machinery, electrical and weapon design; and between meeting operational requirements and the constraints of costs, manning and support activities. One of the most important systems in a modern warship is the main electrical supply and distribution system, which provides the source of power for all systems such as weapons, communication, navigation and steering and ship's systems such as chilled water and propulsion machinery auxiliaries. This paper will therefore be concentrated primarily on this vital system.

The main electrical supply and distribution system cannot be designed in isolation but must be developed within the above constraints, thus ensuring provision of electric power to a multitude of services with acceptable levels of integrity, availability and quality.

The first practical application of electricity afloat in HM warships was in the early 1870s, with the introduction of an electric gun-firing circuit. This was energized by a pile battery which was comprised of 160 elements of copper and zinc plates separated by fearnought and soaked in a mixture of vinegar, salt and water.[1] As might be expected, this proved to be a totally unsatisfactory energy source.

Much has happened since then. The first ship in the Royal Navy to have an electrical supply system was the battleship HMS *Inflexible*. Built in 1881, it had a single d.c. generator operating at 800 V and a strange series–parallel arrangement of arc lamps in the engine and boiler rooms and incandescent lamps elsewhere. This system was similar to that in use at the time in some transatlantic passenger steam ships. Following a not unexpected fatality, the voltage was reduced to 80 V d.c. in 1885; this was to continue until 1900, when the voltage was raised to 100 V d.c. The integrity of the supply and distribution system was improved by installation of a d.c. ring main system and, in some larger ships, the voltage was raised to 220 V d.c.

Although the installed capacity continued to rise, d.c. at 220 V remained the standard of supply for 50 years. It was not until 1946 that a 440 V, 60 Hz, 3-phase a.c. supply was introduced into four of the *Daring* Class destroyers, in line with US Navy practice. This has been the preferred supply ever since.

The design principles for the Royal Navy's electrical main supply system are contained within Naval Engineering Standard 532.[2] The characteristics to which the electrical power supply in HM warships are designed is published in Defence Standard 61.5,[3] which details the quality of supply that will be presented to a user. The method of operating particular ship's systems is defined in the 'Class main supply system' handbook and is also embodied in the ship's standing orders.

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In any design of an electrical system, the various basic modes that a ship can be called on to perform must be recognized:

1. *Wartime action mode:* In this mode, it is necessary to have the maximum redundancy immediately available, such that the effects of damage and/or failure can be rapidly reduced. Response must be at the highest level.
2. *Peacetime mode:* during this mode, interruptions to the main electrical supply system can be accepted, with the exception of a few circuits that are vital to the ship's safety.

Changes in these modes can normally be predicted, unless some unforeseen event such as collision, fire or unexpected enemy action occurs. On present ships, the number of generator sets on load reflects the mode of operation and the acceptability of total or partial loss of supplies.

From the above, one can appreciate the complex nature of a modern warship, with its varying roles depending on its weapons, its seagoing performance and its vulnerability. As has been indicated, there is always a compromise between conflicting requirements and priorities, with the necessity at the end of the day to have a balanced and responsive seaborne weapon system.

In making this compromise we must not forget the men in the ships, who are an integral and essential part of the overall weapon system, being highly skilled both as fighting men and as competent and versatile technicians. The ship is their home and the function of a warship invariably brings conflict between the needs for high technical standards and acceptable accommodation. The prime requirement is for the vessel to prosecute its operational role as a warship and to survive as a fighting and seagoing unit, after encounter with the enemy. Ruggedness is therefore often a more appropriate consideration than sophistication; and ease of repair is usually more important than comfort or recreation. Even in peacetime, the training of a ship's company for war prohibits the regular schedules and steady conditions of the merchant ship.

All these conflicts and compromises have to be taken into account by the electrical power system engineer, who is an integral part of the ship's design team. He must design and develop the electrical power system to ensure that, in all operational circumstances, an electrical supply of the necessary quality and reliability is available to every service in the ship that requires it, thereby enabling the objectives of the ship to be successfully achieved. These, then, are the basic aims of the designer and the following are the major design processes that have to be followed.

THE ELECTRICAL POWER SYSTEM

Estimating load

It will be appreciated that the design of a warship is not an instant process but is the result of many feasibility studies carried out in conjunction with the Naval Staff, to counter a projected threat. As such, it tends to evolve over several years, with weapon and ship systems finally emerging some years from inception of the original requirement.

Figure 1 outlines the growth in electrical connected load during the life of a typical frigate. Early in the design stage, therefore, the electrical power system engineer has to draw up a 'broad brush' load chart (a feature common also to commercial and foreign naval practices), which is primarily the basis for the decisions on the size, number and configuration of primary sources of electrical power for the life of the ship.

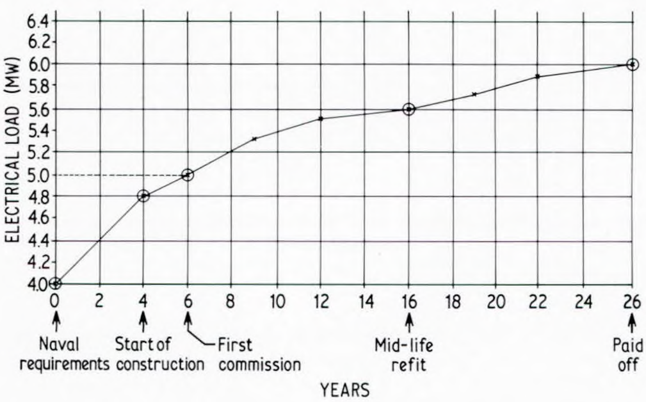


FIG. 1 Growth of electrical connected load from original concept until end of ship's life

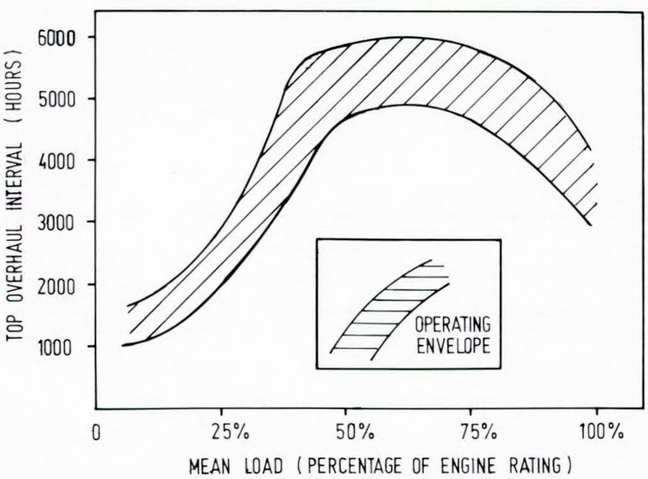


FIG. 2 Relationship between diesel mean load and top overhaul interval

As an example, at this early stage the load chart might indicate that, for a 3000 ton frigate, three or four diesel generator sets would be required, rated between 750 kW–1.2 MW, with one or two switchboards.

The total connected load for the new design is estimated by extrapolation from raw data drawn from similarly sized ships with similar operational roles. This 'broad brush' method is known as the percentage analysis method and, by applying percentage factors to the total connected load, approximate values for total load in each operational state (e.g. harbour, cruising and action) are obtained.

As further consumer data become available, and following consultation with the users, a detailed load chart is compiled. This involves listing each connected load and applying a utilization factor which takes into account the ship's operating state. The mean loads are then summed and a diversity factor is applied to arrive at the maximum load for each operational state. At this stage, growth in the load during both the design phase and the ship's life must be taken into account when deriving the final maximum end-of-life load and in determining the installed generator capacity and size of the generators. In the example considered earlier, the design would be finalized at this stage as, say, four diesel generators of 850 kW rating, split into two diesel generator sets mounted forward with a switchboard and two diesel generator sets mounted aft and separated by three watertight bulkheads.

In practice, the load chart estimation, although being continually updated throughout the life of the ship, is imprecise, erring on the safe side. This could result in considerable overestimation of ship's loads. This overestimation will be exacerbated if diesels are adopted as prime movers, because of their sensitivity to light loading. In this condition, they soot up and the time between overhauls is rapidly decreased. Figure 2 gives feedback of experience from sea and clearly shows how low percentage loading will adversely affect the time between overhauls. Optimum loading is about 70% but, as can be seen, there is a wide variation of approximately 1000 hours over the majority of the range.

It is planned to use statistical methods to predict ships' loads in future designs but this will naturally depend on a detailed statistical analysis of the electrical loading of the most recently designed ships obtained from data-logging equipment; and the data so gathered will be entered into a computer simulation of the ship's main electrical supply system. If the simulation is sufficiently accurate, it will describe the behaviour of the ship's total electrical demand and the individual demands on various points in the main supply system under any defined ship operating condition and at differing times throughout the day. Time will tell how accurate statistical techniques will prove in predicting system loading but data collected will allow the simulation model to be updated and more finely tuned as time goes on and experience becomes established.

Determination of number and sizes of generator sets

Gas turbines are the norm for propulsion of the Royal Navy's warships, although in the new Type 23 frigate there will be a mixture of gas turbines for high-speed boost and diesel-electric drive for economic cruising. Now that steam is no longer used for surface ships, prime mover selection for electrical generation is restricted to gas turbines or diesel engines but, because of the obvious advantages of the latter—independence of any other source of power and ability to be started and put on load at very short notice—fuel-efficient diesels are currently chosen for prime movers.

Before making the final decision on the number and size of generators, it is important to ensure that the estimated maximum total load is correct. Clearly, in the early stages of design this can be difficult but it becomes more evident as the load chart evolves, although the decision would normally need to be taken before the load chart is finalized, and margins must be allowed for future growth during the design and through the ship's life. In the past, traditional methods have proved too generous, resulting in larger and more expensive generators than necessary; and the tendency subsequently to run these lightly loaded has given additional maintenance and downtime problems. In recent years, therefore, considerable effort has gone into ensuring that these margins are kept to a minimum. The final margins will depend, however, on the particular design and the overall ship policy.

Consideration must be given at an early stage to the anticipated fault levels on the system, as these have an intimate relationship with the generator sub-transient reactance. Sometimes (in the interests of using common switchgear throughout the fleet) it is the ability of switchgear to handle the fault current that determines the value of the sub-transient reactance of the generator.

One fact to take into consideration in the selection of generator sets is the behaviour of the ship's electrical load. This can be broken down into a pattern of daily variation and long-term variation. The daily pattern is well-established and has been confirmed by records kept over a period of time under harbour, cruising and action conditions. Not surprisingly, this pattern shows two humps occurring at about mid-morning and mid-afternoon!

The typical shape of the curve of daily variation is shown in Fig. 3. By analysing the variations occurring over a period of time, the limits indicating the long-term variation can be deduced. The day-to-day curve will, therefore, fall within these limits whilst maintaining the general shape. The long-term variation of load can also be shown in the form of a distribution curve. Figure 4 shows the load distribution of a 1 MW generator set on a typical frigate/destroyer; the loads and percentages shown have been taken from actual measurements recorded over a period of time on Royal Navy warships.

The number and size of generating sets and the design of the electrical supply system will be determined by the function, general characteristics and operational role of the ship. It is extremely difficult to lay down hard and fast rules and it will be necessary for each particular design to be judged on its merits; however, there will usually be several combinations of number and size of generating sets that will meet the maximum total load. The selection of the number and size of generators is influenced by a number of factors, which can be outlined as follows:

1. Economical loading.
2. Flexibility of operation to cater for failure/maintenance.
3. Requirement to keep loss of capacity to a minimum.
4. Requirement to install a reserve capacity.
5. High vulnerability of ship.
6. Economical use of machinery space.
7. Necessity to keep switchboard arrangements simple.
8. Necessity to keep system management simple.
9. Minimum loading.
10. Unbalance of loading.
11. Transfer of load via hand-operated or automatic-changeover switches.
12. Maintenance and breakdown margins.
13. Running hours and refit intervals.
14. Availability and reliability.

The number of generators has, therefore, to be another compromise, although in practice the smallest number of sets are installed to meet the requirements.

Methods of operating generators in the ship's main supply system

There are two main methods of operating the generators in the ship's main supply system: 'parallel' and 'split'. In parallel operation, the load is shared by generators operating unattended in parallel on a common busbar; while, in split operation, the generators are operating independently of each other, each supplying a section of the ship's load. In split operation, temporary paralleling occurs only for the purpose of bringing in or changing generators, either on ship or when connecting shore supply.

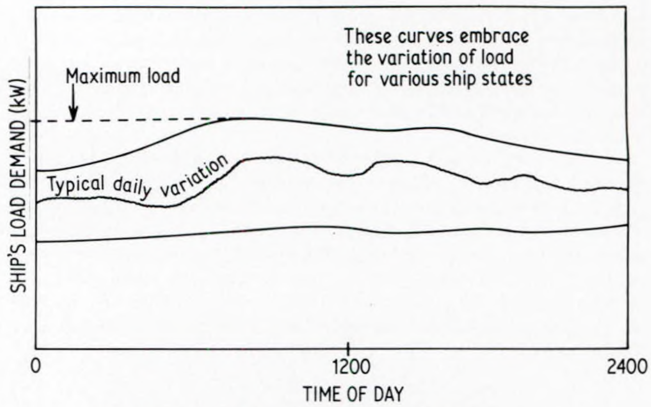


FIG. 3 Typical daily variation of electrical load

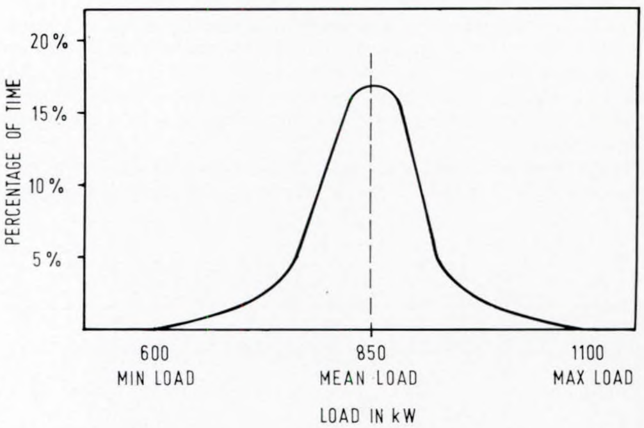


FIG. 4 Load distribution of 1 MW generator set on a typical frigate/destroyer

Split-system operation is the method used in Royal Navy warships such as Type 21s, Type 22s and Type 42s, although parallel operation has been chosen for the new Type 23 frigate. The Type 23, in its prime anti-submarine warfare role, requires quietness at economic cruising speeds and, for this reason, electrical propulsion has been chosen as the main means of propulsion, with gas turbine boost. Feasibility studies demonstrated that an integrated main supply and electrical propulsion scheme would be the most cost-effective solution.

Split operation has been used in the past, since this method of distribution tends to give lower fault levels and greater integrity of supply. When failure of a diesel generator occurs, all utilization equipment or systems supplied from that source lose their electrical supply, whilst essential loads receive an alternative supply via changeover switches which, in turn, have an alternative supply from another diesel generator/switchboard. The incidence of complete loss of supply on the ship caused by equipment failure is, therefore, very low.

Table I: Comparison of split/parallel operated plant

SPLIT OPERATION	PARALLEL OPERATION
1. Incidence of partial loss determined by failure rate of generator set.	1. Low incidence of partial loss of supply.
2. Low incidence of complete loss of power.	2. Low incidence of complete loss of supply.
3. Complex system management and large number of switching operations.	3. Less complex system management and less switching operations.
4. Sufficient capacity required for unbalance and throw-over load.	4. Sufficient capacity required for throw-over load in the event of generator failure.
5. Careful electrical supply system design required to ensure even load sharing.	5. Load sharing determined by governor settings.
6. Fault level limited to two generators in parallel.	6. Fault level limited to number of generators required for full load.
7. Minimal protection required for discrimination.	7. Sophisticated and very reliable protection required for discrimination.
8. Transient response determined by the source impedance of one generator.	8. Transient response determined by number of generators in parallel. (Better than split operation.)

In the case of the Type 23, with its integrated main supply and electrical propulsion scheme, the Ministry of Defence needed to examine its traditional electrical arrangements in order to meet this new requirement and also to meet an additional requirement of reduced manning. As a result, parallel running has been selected for the Type 23, since this method allows a better utilization of installed generator capacity and also meets the reduced manning criterion for this vessel. A split system in the case of the Type 23, with its large propulsion load, was not practical as large system unbalances would have occurred, with generator set loads not evenly matched for the various operating configurations. Improved methods of parallel running protection now give acceptable system performance. Improved utilization of diesel generators gives reduced diesel running hours and a subsequent reduction in the maintenance overhead.

The various points that need to be considered before a decision is taken on whether split or parallel running is adopted are brought out in Table I.

Main supply system arrangement

Due consideration must be given to the geographical siting of the generator sets and associated switchboard and controls, in order to reduce the vulnerability of the ship. Although often constrained by the criterion of ship's stability, this is best achieved by having sufficient dispersal of generating plants and switchboards so as to give a degree of system integrity commensurate with the size of the ship and its operational requirements, whilst also ensuring that, in the event of limited flooding on the ship, enough generating capability remains operational to carry the salvage load.

In the case of a ship with four generators, there will be two switchboards with separation between associated switchboards and generators kept to a minimum. Siting of the switchboards is as important as the siting of the generator sets, since without them there is no means of distributing the power generated to the system. Normally there are at least two watertight bulkheads between switchboards; and the switchboards and generators should be above the level of flooding and preferably be located on the centre line with the same longitudinal separation as their associated generators. If this is not possible, they should be on opposite sides of the centre line but preferably not in a ship's side compartment.

As the secondary control positions of the main electrical supply system are sited in the switchboard rooms, they must be far enough away from the primary control position in the ship control centre (SCC) to ensure that both primary and secondary control cannot be lost by a single surviveable hit. This can readily be seen from Fig. 5.

It is normal practice in HM Ships to sectionalize and interconnect switchboards such that, in the event of failure or action damage to any part of a switchboard, the faulty part can be isolated and the remainder can continue in use. Greater flexibility in loading of generators can be obtained by introducing extra sections. With this arrangement, should one generator not be available the load can be evenly distributed between the remaining generators by suitable grouping of sections (see Fig. 6).

Method of power distribution

In a typical modern destroyer or frigate, there are likely to be four diesel generator sets (each sized, typically, 1 MW) supplying two switchboards, each of three sections connected by bus-couplers. The two switchboards are connected by two interconnector cables with two interconnector breakers at each switchboard. The diesel generators are connected to the switchboard via breakers; and two shore supplies

FIG. 5 Typical four-generator power system in a modern destroyer

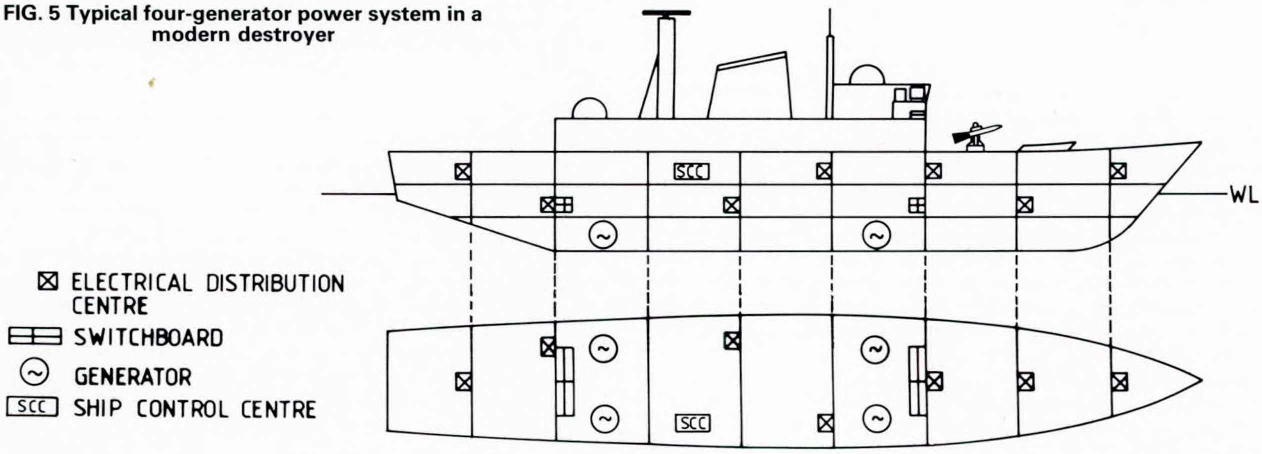
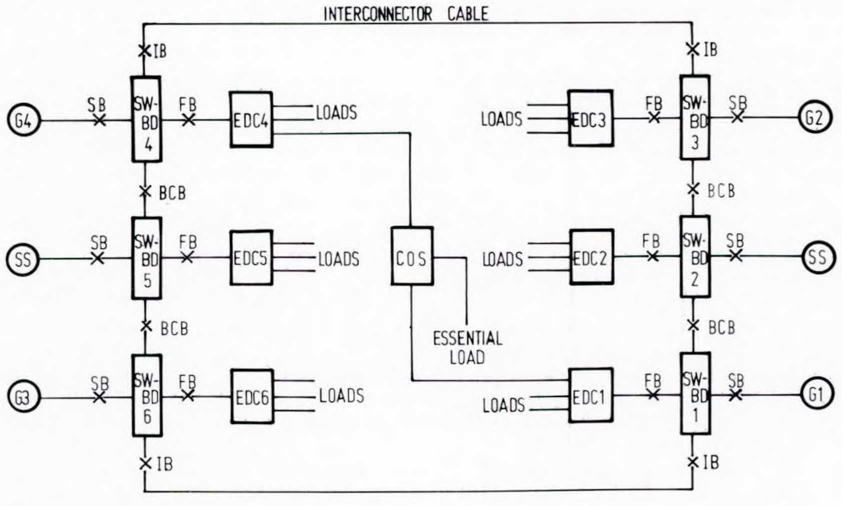


FIG. 6 Switchboard arrangement



ABBREVIATIONS:

BCB	Bus coupler breaker
COS	Change-over switch
EDC	Electrical distribution centre
FB	Feeder breaker
G	Generator
IB	Interconnector breaker
SB	Supply breaker
SS	Shore supply
SWBD	Switchboard

can be connected to the centre sections of the switchboard via shore supply breakers.

Power is distributed throughout the ship in bulk via electrical distribution centres (EDCs) which are sited as near as possible to the electrical centre of the services requiring supplies, and are fed from the three sections of each switchboard by air circuit breakers (see Fig. 7). From the EDCs, power is distributed around the ship to individual large loads, e.g. to individual motors, and to smaller loads via fuse panels and moulded-case circuit breakers (MCCBs) of 250 A and 100 A framesize, arranged in standard panels. The MCCBs offer protection against overload and are readily reset; however, if used on systems whose fault level exceeds 12 MVA for 250-A MCCBs, or 9 MVA in the case of 100-A MCCBs, then the devices must be backed up by current-limiting fuses. Final distribution, to circuits of less than 30 A rating, will be made via HRC fuses, except in the case of induction motors rated above 6 hp, which are supplied directly from an MCCB.

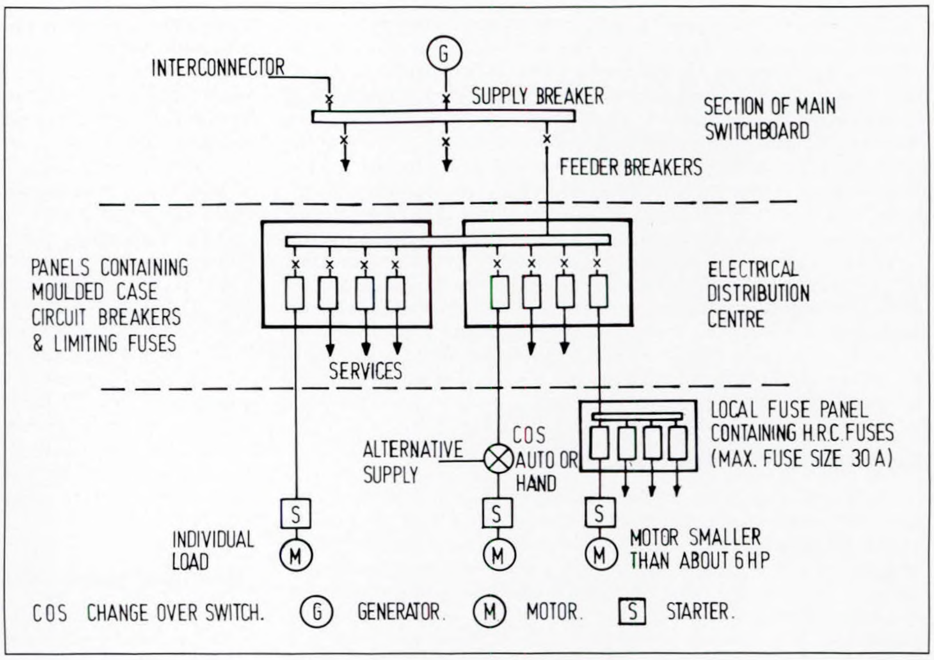


FIG. 7 Typical distribution system

Considerable care is taken in the design of the supply and distribution system such that the current-interrupting devices are rated with regard to the system fault levels and that discrimination is achieved between major and minor devices. This area is dealt with in more detail under the section on protection.

A principal feature of the distribution system for Royal Navy vessels is that it operates with an unearthed neutral point, i.e. there is no direct connection between the neutral and earth. This is chiefly to ensure continuity of supply in the event of an earth fault. In this type of system the earth fault current is so small that a single fault can be tolerated, which is extremely useful under action damage conditions.

In the Royal Navy's ships—as indeed in all navies—certain important services are fed by alternative supplies from different generators and through different switchboards and cables via changeover switches. This is done in order to ensure continuity of service if a generator, switchboard or feeder cable should be lost by action damage; and, for this reason, the changeover switch is placed as near the service as possible.

Changeover switches are of two types—automatic and manual. Auto-changeover switches are used only with vital services (e.g. lubricating oil pumps) and operate to re-connect the service to the alternative source when either voltage and/or frequency-sensing control circuits indicate that the normal supply is outside tolerance. Manual changeover switches, as the name implies, are operated by hand for circuits where some delay is acceptable. Certain weapon systems that require a guaranteed continuity of supply, e.g. supplies to computers, will be provided with a battery-supported conversion equipment.

The development of the distribution system will commence only after the size and number of the generators has been fixed and the configuration of the supply system has been established. The distribution system must perform within specified limits under conditions of steady-state, transient load switching and fault. The whole of the design process is very much an iterative one and each item requiring a supply must be fully identified.

PROTECTION

Protection of an electrical system in a Royal Navy warship is provided for one or more of the following reasons:

(a) To maintain electrical supplies to as much of the system as possible after a fault has been isolated.
(b) To guard the generator and other plant against damage due to abnormal conditions and faults.
(c) To guard the consumer equipment against damage due to abnormal conditions, e.g. a sustained overload.
(d) To isolate faulty equipment and to eliminate the risk of local fire.
(e) To minimize damage to the cable system resulting from the fault.

The main supply and distribution system's electrical plant and user equipment must be protected against damage which may occur through abnormal conditions. These may be grouped into two categories:

- *Condition 1:* Operation outside design ratings due to overloading or incorrect function of the system. This condition can persist for some time and may be acceptable for a limited period, although it may give rise to temperatures outside the design limits for machines and equipment; however, unless these are greatly exceeded, the condition seldom causes sudden or catastrophic failure.
- *Condition 2:* Fault condition, due usually to breakdown of some part of the system. This is acute and arises from catastrophic electrical or mechanical failure or damage. It usually gives rise to very severe excess currents and voltage, which will quickly cause catastrophic failure of any other electrical or mechanical part in the system unless the fault is rapidly isolated. In ships, such damage may not only be accidental but also be inflicted by enemy action and must be taken into account in the design.

The best way to achieve good protection is a selective method of disconnection known as discrimination, which gives isolation as near to the fault as possible and should give minimum disturbances to healthy parts of the system. Protection equipment must be capable of responding to one or more of the following parameters: current, frequency (speed), voltage, temperature and power. It must be time-dependent and is usually adjustable so that the design operating settings can be made to achieve discrimination. The role of a warship is such that a high integrity of supply to consumers under adverse conditions is of the utmost importance and, for this reason, protection for the main supply system must be considered on an overall system basis to ensure that their characteristics are compatible and that discrimination is achieved.

Overcurrent protection

In order to ensure that the nearest 'upstream' protective device will clear the fault, discrimination exists on the main supply system. It can be seen from Fig. 8 that, in the event of a fault occurring downstream of the supply breaker, which incorporates short-time (0.4 seconds) high-current protection and long-time (8 to 20 seconds) low-overcurrent protection, adequate safeguards will be given. The high-current protection setting will be chosen so as not to exceed the short-circuit capability of the generator, thus giving a measure of short-circuit protection. The low-overcurrent protection will ensure

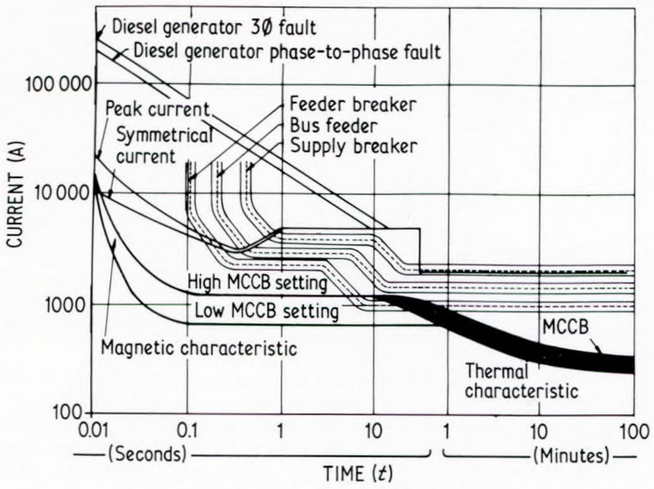


FIG. 8 Discrimination diagram

that sustained overload (kVA), which may result from flooding faults, for example, will not cause damage to the generators.

The interconnector/bus-coupler and feeder breakers are also provided with characteristics similar to the supply breaker but with lower current and shorter time settings. In this way, adequate discrimination is achieved.

It can also be seen that high MCCB settings do not totally discriminate with the feeder breaker for all currents—overlap occurring in the range of 800 to 1200 A. In general, however, short circuits will produce currents in excess of these values and overload will produce currents of lower values and, in practice, discrimination will be achieved. It can further be seen that the MCCBs have electromagnetic and thermal current trip devices. The electromagnetic device gives the required characteristic for short-circuit protection, whilst the thermal device gives the required overcurrent protection characteristic.

The overlap of feeder breaker and MCCB characteristics often occurs because of the conflicting requirements that:

(a) The feeder breaker and all upstream breaker characteristics must be below the generator thermal characteristic in order to protect the generator windings.

(b) The MCCB characteristic must allow a motor to take the motor starting current (and re-switching the current after an automatic changeover switch operation) for the run-up time without tripping the MCCB.

MCCBs used in present ships normally have back-up fuses to protect the MCCB itself against fault currents in excess of their breaking capacity. At these fault currents the fuses will cut off the current, thus eliminating the current to be cleared by the MCCB. Normal faults will be cleared by the MCCB with the fuse remaining intact.

To improve interconnector cable fault protection and discrimination, unit or differential protection can be applied between each pair of interconnected breakers. To provide stator fault protection on the generator, unit protection can be applied between the generator star point and the supply breaker.

Overvoltage protection

Sustained overvoltage conditions, which may occur in the event of an automatic voltage regulator (AVR) failure or loss of voltage-sensing, are normally protected with an overvoltage protection unit (OVPU), fitted in the AVR circuit to open the field circuit of the generator in the event of an overvoltage occurring.

The OVPU is designed to discriminate between transient overvoltage conditions caused by system faults and permanent overvoltage conditions.

Undervoltage protection

All supply, interconnector, bus-coupler and feeder breakers are fitted with an undervoltage trip facility. The undervoltage trip delay must be greater than the time of operation for the protection of overcurrent faults, which could reduce bus-bar voltage to undervoltage trip level, in order to ensure that discrimination is achieved.

Overspeed protection

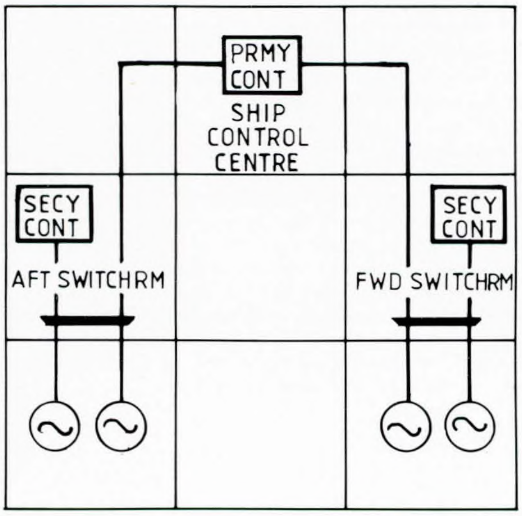
This is normally fitted to prime movers, and set at an overspeed of, typically, 15%, with a mechanical operation to cut off the fuel and thereby stop the diesel. It is not standard practice to fit overfrequency electrical protection.

Underspeed protection

AVRs are normally fitted with a low-frequency inhibit feature to prevent nominal supply voltage being maintained if the frequency falls below 80% of the norm. This ensures that magnetizing currents for motors and transformers are limited to an acceptable value.

Reverse power protection

This is only fitted in parallel-operated systems and ensures that the prime mover is not damaged due to back driving. It also reduces the probability of the healthy generator being tripped due to an overload.



PRIMARY CONTROL ALLOWS
1. Starting and control (voltage and frequency) of all generators.
2. Synchronization of any generators.
3. Control of all main switchgear and indication of state of whole main supply system.
4. Communication with main switchboard.

SECONDARY CONTROL ALLOWS
1. Control (voltage and frequency) of own generators.
2. Synchronization of own generators and on to remote switchboard.
3. Control of own main switchgear and indication of state of whole main supply system.
4. Communication between control and other switchboards.

FIG. 9 Main supply system control

POWER SYSTEM CONTROL

Control of the main supply system is from a primary control position located in the ship control centre (SCC), in which will also be located the main machinery plant control system (see Fig. 9).

The whole electrical power supply system is supervised and controlled from the SCC, including the remote-controlled starting of the diesel generator sets; control of the voltage and frequency, and the synchronization of generators for parallel running; together with the control of all main switchgear with full indication of breaker states on a mimic diagram of the main supply system. Secondary control of the main supply system is available at switchboards; however, under normal operating conditions these spaces are not manned. Control of the air circuit breakers is exercised at the secondary control position for that switchboard only—indication being provided, however, of the breaker states at the second switchboard.

The aim of central control is to cater for:

(a) Even distribution of load between generators.

(b) The isolation of defective parts of the system and the re-direction of supplies to important services.

(c) The co-ordination of electrical supplies and repair parties in the restoration of power to damaged areas.

The operation of the main supply system from the SCC has proved to be very effective and it is generally considered that the system information available, together with the degree of control available, is adequate for normal system operation. When failure of plant occurs, however, insufficient information is available within the SCC to make a full and proper judgement as to the cause of the failure and, inevitably, the failed equipment must be examined locally by a watchkeeper.

QUALITY OF POWER SUPPLIES

Correct function of equipment can only be measured when the power supply is within the limits worked to in the design of consumer equipment. In order to achieve this, power supply characteristics must be maintained within declared tolerances. The detailed characteristics are given in Defence Standard 61–5 Part 4,[3] which lists power supply tolerances in ships and submarines.

Disturbances of the power supply are caused mainly by consumer equipment and are propagated, via the supply network, to other consumers. The extent of the disturbance depends on interaction between consumer, distribution system and generating plant. The quality of the 440 V main electrical supply, together with transient occurrences that may be expected, can be summarized as follows.

Voltage

Nominal voltage	440
Load range tolerance	
(a) Average line-to-line value of 3-phase system	±5%
(b) Line-to-line voltage of single phase of 3-phase system	±6%
Maximum unbalance	2%
Maximum modulation	2%
Transients (average line-to-line value for 3-phase system)	
(a) Frequent transients (10 times per hour)	+6% −10%
Recovery time 0.5 seconds.	
(b) Infrequent transients (10 times per 24 hours)	+10% −15%
Recovery time 1.0 seconds.	
(c) Rare transients (typically once per week)	+23% −40%
Recovery time 5 seconds.	

This can be compared with Lloyd's Regulations of +6% and −10% voltage fluctuation at rated frequency.

Frequency

Nominal frequency	60 Hz
Load range tolerance	±2.5%
Constant load tolerance	±0.5%
Modulation	0.25%
Infrequent transients (10 times per 24 hours)	±3.75%
Recovery time 2 seconds.	
Rare transients	+12% −10%
Recovery time 6 seconds.	

This can be compared with Lloyd's Regulations of ±2.5% frequency fluctuation at rated voltage.

Waveform

Maximum individual harmonic	3%
Maximum total harmonic content	5%

Harmonic distortion of the supply voltage waveform is caused by the volt drop resulting from the flow of harmonic currents through the system impedance. Many types of equipment draw harmonic currents but, in ship's systems, significant distortion is associated mainly with power conversion or control by solid-state devices.

The effect of waveform distortion on a Royal Navy shipborne power system is acute, since a comparatively high proportion of the load is rectified and the system is finite. Rectifying and static inverting loads, when connected to the supply network and fed with a sinusoidal alternating voltage, do not draw a sinusoidal alternating current, due to their non-linearity. The distortion in the waveform current drawn from the a.c. supply system is due to components at harmonics of the supply frequency. A distortion of the waveform can cause interference effects on communication systems and interfere with the operation of devices and equipments, particularly those that depend upon sinusoidal waveform voltage for correct operation, e.g. point on wave control. Harmonic currents, besides being a source of interference, also have other detrimental effects such as lowering the power supply input power factor, reducing motor efficiencies and causing increased heating.

Levels of 5% total harmonic distortion (THD) and 3% for an individual harmonic are the maximum accepted system voltage distortion values for the main supply system in Royal Navy ships. The maximum allowable THD at the generator terminals at no load is limited to 2%.

The amount of distortion that a load (or series of loads) will apply to the main supply system is dependent upon the equipment's harmonic current demand and the source impedance (the latter will vary with type of generator, distribution system and ship loading). In order to ensure that the system voltage THD levels are not exceeded, the voltage distortion that equipment is normally allowed to produce at its terminals is limited to 3% THD and 1.5% individual harmonic content, to allow for the summating effects of a number of individual distorting loads.

Whilst harmonic distortion problems can be largely attributed to non-linear electrical loads on a finite system, a further problem of waveform modulation can exist and is largely caused by pulsing electric loads, such as high-power radio transmitters, radars and large compressors. Voltage modulation is also evident in the no-load generator output voltage, but this can generally be ignored.

In order to minimize modulation effects in the distribution system, one must ensure that the demand due to pulsing loads at any point in the network does not exceed 20% of the maximum under normal operations; and, if possible, individual loads should be no greater than 5 kVA. Outside this category, individual calculation is necessary and the summation of modulating loads must be based upon statistical techniques to yield probabilities of coincidence.

Table II: Converted supplies and their typical services

SUPPLY	CONVERSION	TYPICAL SERVICES
24 V d.c.	Transformer rectifier unit (TRU)	Gyro/magnetic compasses; ship inertial navigation system (SINS); Radiac system; sonar; propulsion machinery control systems.
28 V d.c.	TRU	Aircraft starting/servicing supplies.
24 V d.c. (filtered)	TRU + battery back-up	Internal voice communication systems.
220 V d.c.	TRU	Degaussing; guided weapon system (GWS); sonar.
115 V, 60 Hz, 3-phase	Transformer	Sonar.
115 V, 60 Hz, single-phase	Transformer	Lighting, portable apparatus; drum direction system; main broadcast; conning intercom; EM log; sonar; external communications; anti-condensation heaters.
115 V, 400 Hz, single-phase	Static frequency changer (SFC)	Data transmissions; SINS; gyros/magnetic compasses; sonar; radar, Navaids.
115 V, 400 Hz, 3-phase	SFC	GWS; sonar; gyro compasses.
200 V, 400 Hz, 3-phase	SFC/rotary convertor	Computer supplies; aircraft starting; servicing supplies.

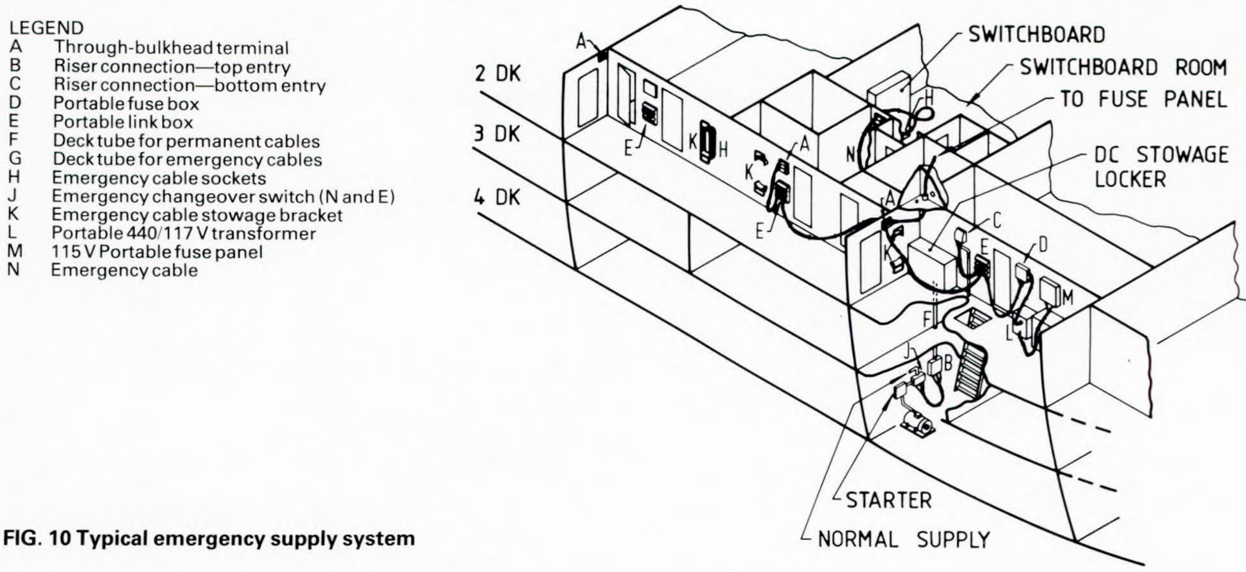


FIG. 10 Typical emergency supply system

Electromagnetic interference (EMI)

With the large number of systems and closely bunched cable runs, together with tightly packaged miniature electronic equipment, it must be assumed that EMI will be a significant problem if steps are not taken to attenuate it from the outset of the design. The Royal Navy's experience has been built up over the years and acquired the hard way, by filtering out the problems as they arose. As a result of this experience, in modern warship design great stress is given to applying sound installation practices for cable routeing and isolating sensitive equipment and cables and suppressing EMI generators at source. Only in this way can compatibility be achieved between equipments and systems. Suppression of interfering frequencies to sensitive equipments should only be carried out as a last measure.

As data transmission and computation of information become more widespread, the EMI levels will of necessity become lower and even more care will need to be taken with EMI. In the Royal Navy this stage has already been reached but commercial marine ships, because they have more space available, have yet to be concerned—this enviable position will not last for long.

Converted supplies

Although the main supply and distribution system is one of the most important systems on a Royal Navy warship, there are numerous other electrical systems derived from the main supply system. These are defined as converted supplies, which are obtained from rotating machinery, transformers, rectifiers or static frequency changers.

Converted supplies may be broadly divided into three groups:

(a) General lighting, small power and portable apparatus (115 V single-phase).

(b) Control and communications (24 V d.c.; 28 V d.c.; 220 V d.c.; 115 V, 400 Hz single-phase and 3-phase; 200 V, 400 Hz, 3-phase).

(c) Aircraft starting and servicing (28 V d.c.; 200 V/400 V, 400 Hz, 3-phase, 4-wire).

Table II gives some indication of the many converted supplies that have been provided together with their typical services.

Present practice for frequency conversion is to use static frequency changers up to about 10 kVA and motor generators over about 10 kVA. Transformer rectifier units are used for conversion from a.c. to d.c. and transformers are used for change of a.c. voltage without an associated change of frequency. It is now Director General Ships' policy to encourage the sole use of the ship's main 440 V 60 Hz supplies for all equipments.

Conversions of inputs to other types of supply are carried out within the system or equipment. In this way, the requirement for converted supplies from a central and remote source is minimized and a higher integrity is thus assured. This principle is accepted by both Ship and Weapon Departments and is the declared NATO aim as defined in STANAG 1008,[4] namely: 'equipment is not to be designed to operate on a converted supply if 440 volts 60 Hz will suffice'. This policy was necessary as, in the past, too many 400 Hz users called up high-frequency power supplies in order to minimize the size/weight problems of their individual equipments. This short-sighted and expensive practice has been stopped as, too often, the 400 Hz supply was rectified and the harmonic currents thus generated caused distortion of the voltage waveform, to the consternation of other consumers.

Emergency supplies

As well as alternative supplies, modern Royal Navy warships also have an emergency supply system, which supplies essential services following major action damage. There are three priorities—float, move and fight.

1. *Float:* Pumping and fire-fighting equipment; lighting and internal communications, and flood alarms.
2. *Move:* Auxiliary services to main propulsion units and control of main propulsion and steering, plus sick-bay facilities.
3. *Fight:* To provide a limited defence capability, such as close-range defensive weapons.

The emergency supplies are typically provided as shown in Fig. 10, which shows the major components. These emergency supplies are taken from MCCBs on the switchboards via flexible cables, through sockets in bulkheads for horizontal runs and through vertical risers between decks, where they are finally connected to the important load.

CABLES

No discussion on electrical system design would be complete without mention of the cables that are necessary to control and conduct the current generated and distributed. One means of appreciating their importance is to consider that in a pre-war battleship there were 300 miles of cabling; whilst in the present-day *Invincible* Class there are over 1000 miles. This increase applies to all present designs of Royal Navy warships and the complexity can be directly related to connections. In a Type 42 destroyer there are 250 miles of cabling and 200 000 connections; the weapon system is the largest contributor to this statistic, with 5500 cables and 125 000 connections. This is followed by the internal communication system, with 670 cables and 20 000 connections; and machinery control, with 900 cables and 12 000 connections.

There are many types of insulating and sheathing materials available for cables to meet the various environments and requirements that

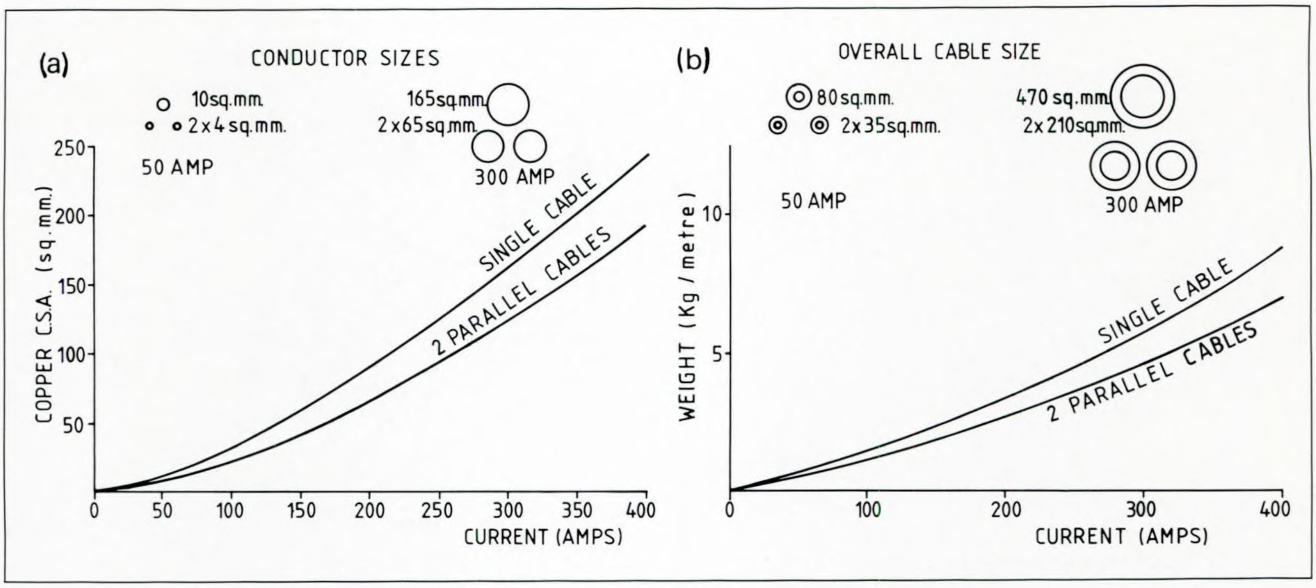


FIG. 11 Single vs. parallel cables: (a) current/conductor CSA; (b) current/weight

occur in a warship. These are listed in Table III, together with their characteristics.

The majority of cables, although fire-resisting, will, in a fire, produce smoke and, in some instances, toxic and acid gases. After considerable involvement with the cable manufacturers, the Royal Navy has now introduced a policy for a rationalized range of limited fire hazard (LFH) cables, which will be introduced in all new designs of RN warships. As the name implies, these cables will be flame-retardant, will generate low amounts of smoke, and have low toxicity and low acid gas content.

As modern warships become more and more complex, the number and weight of cables is an ever-increasing problem. In a typical 4000 ton ship, the cables weigh 118 tons and the associated support system and glanding another 23 tons. Clearly, any means to reduce cable weight would be an advantage to the ship designer and one of the secondary benefits of LFH cable is that, in sizes up to 2.5 mm^2 cross-sectional area (CSA) (which represents 80% to 90% of all cable length installed), lightweight thin-wall insulation and sheathing has been possible, thereby drastically reducing the weight and volume of the majority of cables, with a pro rata reduction in cable supports and glanding. In a typical frigate this can amount to a saving of about 25 tons, which can be invaluable to the naval architects for stability of the vessels or, operationally, might permit the installation of an additional weapon system.

The weight and size of power cables are predominantly determined by the weight of copper but there is an advantage in the weight reduction to be had by using two or more paralleled cables and taking advantage of the higher current densities available as the CSA of the copper gets smaller (due to thermal geometry). Thus, particularly in the larger cables, considerable reductions can be made in the CSA of the copper by paralleling cables to carry the same current as a single large cable. This weight advantage is indicated in Fig. 11 (although there is not much difference in overall cable sizes as insulation is a constant thickness) but if the CSA is reduced too far then volt drop considerations prevail.

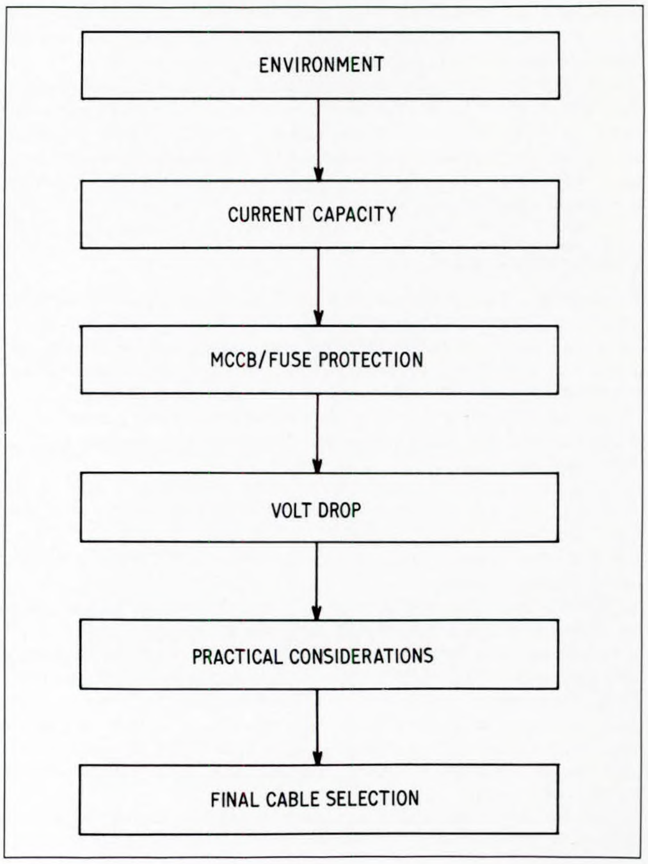
Table III: Conductor insulation

MATERIAL	CHARACTERISTICS
1. Ethylene propylene rubber (EPR)	General purpose; average physical resistance; maximum temperature 85°C
2. Polyethylene (PE)	Used extensively in high-frequency; average physical resistance; maximum temperature 50°C
3. Chlorosulphonated polyethylene (CSP)	Poor electrical properties; good heat resistance and flexibility; maximum temperature 85°C
4. Silicon rubber	Reasonable electrical and physical properties; maximum temperature 105°C
5. Polyvinyl chloride (PVC)	Good electrical and physical properties; combustion byproducts are extremely corrosive and toxic; maximum temperature 50°C

Cable selection sizing

In selection of cable sizes for generation and distribution, due care must be taken and reference made to Ship Department's policy and installation (NES 513 and NES 502).[5,6] This is best appreciated by reference to Fig. 12, which enables a cable size to be determined in

FIG. 12 Constraints on cable selection



relation to the predominant selection factor. As an example, in the design of the Type 22 frigate, 45% of cables were sized by current-carrying capacity, 45% of cables were sized by considerations of voltage drop and 10% of cables were sized for MCCB/fuse protection reasons.

THE WAY AHEAD FOR ELECTRICAL SYSTEMS

The main supply and distribution systems described in this paper have evolved over the years, from the initial installation of d.c. systems in Royal Navy vessels to the present-day a.c. systems. To date, the latter have proved acceptable but they do have some known shortcomings, namely:

(i) Information to operators and maintainers is limited in scope and is only available at the switchboards.
(ii) Operation of the system requires a high degree of skill.
(iii) Load balance between the generator and switchboard is very difficult to achieve with a split-system design.
(iv) Prolonged light loading of diesels during action stations or exercise.
(v) Limited duplication of supplies to users.
(vi) Total manual operation; hence high training load and operator-induced errors.

The shortcomings outlined above were to some extent overcome in the designs of the Type 21 and Type 22 frigates and the Type 42 destroyer, in which electrical distribution centres (or load centres) were adopted. This improved the diesel/switchboard loading and provided power system information in the SCC. Since 1977, however, studies have been carried out both intra- and extra-murally to determine the optimum design principles to be adopted in future escort ships, especially in view of the ever-increasing demands to reduce manning levels and, thus, through-life costs.

The results of the studies led, in 1979, to the issue of a Procurement Specification for Main Supply Systems for Future Escorts. The essential features of this Procurement Specification were the adoption of parallel running for all electrical prime movers; a large number of load centres (dual-fed where necessary), nearer the user of power; and automation of those functions where it had been shown that an operator is either prone to errors or where speed of response is critical.

An additional advantage of the proposed method of implementation was the provision of additional plant information, to enable incipient plant failures to be recognized. This tied in with the proposed secondary surveillance system for propulsion and auxiliary plant. At the same time, developments in the Engineering Branch of the Royal Navy meant that the responsibilities for the maintenance and operation of the main supply system now fall within the sphere of influence of the Mechanical Engineering Branch. It is not within the scope of this paper to discuss the wider-ranging implications of this transfer of responsibility; suffice it to say that, functionally, the main supply system can now be considered as one of the propulsion or auxiliary control systems and there are significant pressures to adopt higher degrees of automation to allow the main supply system to be operated by Mechanical Engineering staff as well as their other tasks.

It is confidently expected that the adoption of greater automation will result in significant savings in the procurement costs of the main supply system. For instance, in one ship design (for a ship which was eventually not built), there was a saving in cost of diesel generating plant of some 30%. Such savings need to be offset against the cost of the automatic controls but, if one diesel can be saved in each ship, then it can be clearly seen that the potential savings for a class of ships can be considerable.

It is not intended to discuss current ship designs in any detail but it can be disclosed that the Type 23 will employ sophisticated main supply system controls, with automatic synchronizing; real and reactive power sharing; extensive parallel protection features, and a significant amount of dual feeds to essential supplies. It must not be thought that the adoption of a parallel main supply system removes all problems; there is a significant increase in prospective fault levels and this does cause some problems in selecting distribution equipment.

CONCLUDING REMARKS

I have attempted to describe only the major processes that must be followed and understood in coming to a successful electrical power system design for Royal Navy warships. The limitation of space has greatly constrained description and it is hoped that in this paper I have demonstrated that a modern warship is extremely complex and must be designed as a total system whilst giving cognizance to the many unique and often conflicting constraints and limitations that are present and which have to be balanced before achieving a complete and acceptable (to all parties) design.

For those of you who require more detailed information I refer you to Refs 1 and 2.

ACKNOWLEDGEMENTS

The author wishes to thank his colleagues within MOD for assistance and advice willingly given in preparing this paper, particularly J. Shepherd RCNC.

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Discussion

DR P. J. GATES (Dept of Mechanical Engineering, University College London): I should like to congratulate the author on his comprehensive outline of the philosophy of the power systems of RN warships and, especially, the insights he has given us of the design of the power system for the Type 23 frigate.

All marine electrical power systems must be designed to take account of many factors not found in land systems; but warships' power systems are by far the most complex, exhibiting in a single system most of the problems one could envisage in the supply and distribution of electricity. In recent years, for warships, there has been a dramatic growth in crucial weapons' electronics which depend on high-quality, high-integrity electrical power systems. The decisions which have to be made in specifying, designing and procuring the power systems depend on the balance of a large number of important, independent factors. The resulting characteristics vary as different constraints are placed upon those responsible for procuring the warships.

In addition, the relentlessly changing technology at the disposal of these engineers also demands continuous re-evaluation of the philosophy to ensure the most appropriate solution is used—the move to parallel running cited in the paper being a recent example. The author describes extremely well in his paper the key characteristics of the electrical power systems of warships currently on the drawing-board and some of the reasoning behind their philosophy.

University College London began, in October 1982, a new MSc course in Marine Electronic and Electrical Engineering to complement its existing MSc courses on naval and marine topics (Marine Mechanical Engineering, Naval Architecture and Ocean Engineering). Lectures on marine power systems, of both merchant ships and warships, are an integral part of this course. We believe that this set of lectures is unique and no other university is teaching the theory of power systems as applied to ships. Whereas much has been published openly on merchant ships' systems, Mr Scott's paper is the first for a number of years to cover comprehensively warship systems.

I should like to make two observations about the design of electrical power systems in warships which I believe this paper illustrates. First, as the naval architects keep telling us, 'ships are different'. Traditionally, courses on electrical power systems have concentrated on infinite busbar theory, which is a good approximation for the national grid but not for ships. The courses often gloss over effects (such as system capacitance to earth and the effects of large distorting loads) which may not be of paramount importance for a large land installation but which may dominate the considerations of ships' systems. Additionally, the factors influencing decisions (such as those outlined in the paper for the choice of the number of generators) are, for ship systems, completely different to those which normally apply for land systems. It is for this reason that University College considered it essential that a new series of lectures on marine power systems be initiated, instead of using existing lectures biased heavily towards the needs of the land systems.

Second, it is interesting to compare the complexity of the design process for the system with its operation (in this context, design is taken to mean the whole process—feasibility studies, specification, detailed design, procurement and oversight of building). The operator is presented with a system, all the design decisions having been made, and often with an operating philosophy implicitly or explicitly based upon these decisions. Undoubtedly there will be details which will be good and bad, and liked and disliked; reports from operators on these aspects are an important part of the design process. Compared with other systems, a ship's electrical supply and distribution system is very reliable and, except for the prime movers, requires little maintenance. As a consequence, in the RN, the operators responsible for propulsion and other auxiliaries are now also responsible for the power system. I hope that it will be realized that the design process is complex and linked irrevocably to the major users of ship's load, the weapons systems, and that the division of labour appropriate to the operators is not necessarily appropriate for the engineers involved in the very different business of procurement.

In the paper it is incorrectly stated that weight savings resulting from low fire-hazard (LFH) cables are invaluable. The factor which distinguishes ships from aircraft is their ability to carry significant loads economically. Weight savings, whilst being valuable, are not invaluable. Modern warships are in fact volume-limited, not weight-limited, in design[a] and savings in weight cannot necessarily be turned to advantage where they are not accompanied by savings in deck area. Even when they can be exploited, it is fallacious to believe that a saving of, say, 25 tons can mean that an additional weapon system of this weight can be embarked. Every ton of additional weapon system can add several tons to the displacement of the ship, through increases of size of supporting service systems and facilities for the additional complement required to operate the weapon system. Provided that the weight of equipment is accurately defined early in design, savings of weight are unlikely to be significant unless associated with usable volume reductions. The only exceptions are items which have a disproportionate impact on stability, such as radars and other mast-mounted items.[b]

Once a design is progressed to a stage where the principal dimensions have been irrevocably frozen, however, it is a different matter. If ships undergo modernization—and it is no longer MOD policy to modernize ships[c]—weight savings are far more valuable. For a number of reasons, not least of which is economy, ships are not built with large margins for additional weight and stability and, consequently, it is difficult to embark *major* additional weapons systems during the ship's life. If required, it is *technically* possible to accommodate any number of weapon systems in the initial design, but adding them later can be a nightmare.

Those responsible for the electrical power systems must be able to define accurately the parameters of the system at an early stage in the design of the ship—and this requires considerable skill and experience. It is essential to keep to the weight budget during the project and weight increases after the preliminary stage can be a major problem. Over-specification, as against accurate specification, is not the simple answer to tight budgets as this can result in other failings, such as an increased maintenance load due to light-load running of generators.

Although the weight savings may not be significant, the use of LFH cable for good operational reasons should be welcomed. As far as the power system is concerned, however, there is a disadvantage. The thinner insulation, which allows weight savings, means that the conducting cores of adjacent cables are closer together and consequently have an increased mutual capacitance. This increased capacitive coupling exacerbates the interference problem. I should like to ask the author what steps are taken to reduce this problem and what effects it will have on the electromagnetic compatibility standards for equipment.

The quality of electrical supply which the power system designer is beholden to provide in warships is well specified and described in the paper. This high-quality supply is expected by those who design equipments which will use that electrical supply (the naval equivalent of consumers); however, the quality can only be maintained if the characteristics of these user equipments do not exceed certain limits—that is to say, if there is a compatibility of supply and use. I should like to ask the author to outline the limitations imposed upon warship equipment to enable designers of the power systems to meet the tight specification for the quality of the electrical supply.

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J. K. ROBINSON (Chief Electrical Engineer, Scott Lithgow):

Load analysis

It is our opinion that the growth margins specified by MOD, rather than the method of load chart estimation, have been the major factor contributing to low diesel-engine loadings in service. It is noted, however, that the specified growth margins have come down from 20%, via 20% excluding heating and lighting and air conditioning, to 10% (excluding heating and lighting) in tender enquiries over the past 10 years.

With a large fleet consisting of many types of vessels and standardized ranges of generating sets, what use is made of the transfer of refurbished engines between vessels at refits to cater for load growth?

In view of the aim in commercial vessels of improved overall efficiency and the use of waste-heat exchangers, would the author clarify why recent MOD tenders have specified all-electric heating?

Generator ratings
What system power factors are recorded in service by the data-gathering system? In recent offshore vessels, we have supplied generators at 0.85 power factor where there was a large electrical heating load, and generators at 0.6 power factor to avoid light-load running of the engine where there was a large thyristor load.

The penalty for specifying high sub-transient reactances, in order to achieve low fault levels, is poor motor-starting capability. No mention is made of the basis of selection of type of motor-control gear or low-starting-current motors to ensure that transient voltage dips are within the tolerance of supply quality.

Distribution
We are surprised to find MOD ships still being designed with combination low-fault-capacity MCCBs with back-up fuses, when current-limiting MCCBs with breaking capacities of 51 MVA are readily available.

Do the MOD see any advantages in the use of local motor-control centres for their EDCs, which are standard practice in the offshore oil industry, rather than individual starters?

Protection
What protection is being considered for the parallel operation of generators in the Type 23 design?

If one generator AVR fails to zero output, then its associated machine can still deliver useful power (depending upon the ratio of direct-axis to quadrature-axis reactances) to the system whilst another machine is run up and paralleled.

If, however, one generator AVR fails to full output, the large reactive current circulating between generators may result in the healthy machine tripping on overcurrent and the unhealthy one immediately thereafter tripping on overvoltage, resulting in total system failure.

Most marine generators have a fairly short thermal time constant on their rotors, e.g. 5 min, and, as 80% engine speed would require a nominal 125% excitation current, presumably one should fit an inverse time characteristic underspeed protection device to trip the (pilot) excitation.

What automatic load-shedding arrangements are generally fitted to cater for gradually increasing load in single-generator operation; and for sudden loss of a second generator running in parallel, as may occur on the Type 23?

Quality of supply
UK-registered cargo vessels are required to meet Statutory Instrument No. 572 (1981) which, via Merchant Shipping Notice No. 965, calls up the IEE Ships' Regulations and relevant British Standards. These standards, e.g. BS 2949 clause 42 for generator voltage regulation or BS 5514 part 4 for diesel-engine governing, result in the power systems of commercial vessels having the following generation performance limits:

Voltage:	Steady state	±2.5%
	Maximum unbalance	2%
	Transients	
	(frequent or rare)	+20% −15%
	Recovery time 1.5 seconds.	
	Waveform deviation	10%
Frequency:	Speed droop	5%
	Steady-state speed band	0.8%
	Transients (frequent or rare)	+10% −10%
	Recovery time 8 seconds.	

Thus it would appear that the inherent machine characteristics and speed/voltage closed-loop control performance are not significantly more onerous in MOD vessels, except perhaps in the quality of the waveform. As the majority of the larger 440 V consumers, e.g. auxiliary motors, are relatively insensitive to waveform quality, and those that are sensitive generally use converted supplies, is not the 440 V waveform tolerance in Defence Standard 61–5 Part 4 unnecessarily restrictive?

Many offshore vessels have thyristor-fed d.c. motors with a capacity of about 50% of the system total load and these may pulsate for long periods; for example, consider a 3000 hp draw-works load when 'tripping' drill-pipe to change the tool bit with the hole at 15 000 ft. Generally we avoid waveform problems by having low source impedance generators, and transformers separating the standard 600 V a.c. input to the SCRs from the general 440 V distribution system. The MOD propose motor/generator sets in the Type 23 to convert from 600 V to 440 V a.c. As this is obviously a more costly arrangement than transformers, would the author clarify for which of the following criteria was there an advantage in using motor/generator sets: weight, deck space, efficiency, maintenance, noise, vibration, waveform quality, voltage regulation, fault level and motor starting?

We have not experienced any problems with overheating of motors due to harmonics but these have occurred on large transformers, feeding thyristor drives, where their capacity and temperature-rise type tests were only to BS 171.

EMI
There is concern regarding EMI in commercial ships and this has been recognized by the IEE Ships' Regulations Committee, which published in 1982 a guide in the form of Appendix 7 to their Regulations.

Are the MOD considering the use of fibre optics for the Type 23 and, if so, is it only because of immunity to EMI or is the level of data transmission such that the greater information-handling capacity is needed?

Cables
From the figures in the paper, some 78% of cable power is non-power transmission; thus there would appear to be considerable scope for saving in weight and combustible material by integrating weapons, communications and control systems by the use of microprocessors for multiplexing linked by a duplicated ring-main data-highway system.

Table III notes the temperature limit for PVC as 50°C. A heat-resisting type with a maximum permitted conductor temperature of 75°C (Lloyd's Register) is readily available.

Whilst agreeing with the MOD's aims in introducing LFH cables into warships, we would note that thin-wall insulated wires cost more to purchase and installation time and labour costs are also increased because of their inherent springiness and more onerous *Q.A* requirements.

Disadvantages of using single cores in parallel for three-phase circuits are that more installation labour is required for reeving and securing and more space is needed for bulkhead glands. Also, if there are more than two cores per phase, the current-carrying capacity is reduced owing to bunching factors (unless the cables are spread apart for cooling purposes, in which case they would no doubt leave insufficient space for the pipes and ventilation trunking in the alleyways).

As shipbuilders, our general policy is to investigate the use of single cores in parallel for circuits requiring more than 125 A per phase.

We are surprised at the high proportion of cables sized by voltage-drop considerations. Is this not due to an excessive amount of power being transmitted at too low a voltage? A three-core 2.5 mm^2 cable at 440 V would have to be about the length of a frigate before voltage drop became the limiting factor.

P. T. CHILMAN (Lloyd's Register of Shipping, Glasgow): I have read with interest Mr Scott's paper, which is concise in its overall description of the topic and yet detailed in certain areas, such as choice of cable types. My experience is almost totally of merchant ships with some involvement in Royal Fleet Auxiliaries and specialized Royal Maritime Auxiliary Service and Royal Navy Ships, all of which were built to commercial standards. I have certain points to make on the paper which I shall list under Mr Scott's chosen headings.

Estimating load
In merchant ships, the most difficult work in installing additional cables is passage of them through ducts in decks and bulkheads. Quite often the fire-sealing of the ducts is carried out with a setting compound. Further, regarding the prevention of passage of fire between machinery spaces and accommodation areas, and between accommodation areas themselves, the bulkheads are termed as 'A' and 'B' Class (the latter being almost exclusively in accommodation areas), as required by the 1974 SOLAS Convention.

'A' Class bulkheads are steel and are insulated on one side. They are designed to prevent the passage of smoke and flame for one hour and to prevent the average and point temperature rises exceeding 139°C and 180°C respectively at the end of a specified time depending on the spaces involved. 'B' Class bulkheads are made of non-combustible materials. They are designed to prevent the passage of flame for half an hour and to prevent the average and point temperature rises exceeding 139°C and 225°C at the end of a specified time depending on the spaces involved.

Would Mr Scott please say if RN ships have bulkheads similar to 'A' and 'B' Class and are ducts packed with a setting compound? If the answer is yes to either or both of these questions, is much trouble experienced when new, additional cables are installed as the electrical connected load increases?

Method of operating generators in the ship's main supply scheme

In merchant ships, the parallel method of operation is generally accepted. Normally three generators are installed, one being sufficient to supply the ship's normal sea-going load and two being operated in parallel when docking and undocking and when manoeuvring in confined waters. The third generator is installed to satisfy the classification society's requirements that there must be sufficient generating capacity to ensure operation of essential services with one generating set out of action.

During parallel operation, failure of one generator does not result in loss of power to essential services.

In RN ships using split-system operation and having two generator rooms, does this mean that all generators must be running and connected during docking and undocking? If one generator supplying a section of the ship's load fails, how quickly can supplies be restored?

Method of power distribution

On first reading the paper, Mr Scott's statement that RN vessels operate with an unearthed neutral point implied to me that a neutral connection was made with the generator star point. On reflection, I now see that this is not the case and that RN ships use the three-phase, three-wire insulated system of distribution. This is the most common method adopted in merchant ships since with the neutral earthed, as Mr Scott points out, failure of supplies to essential services can occur on an earth fault since the short-circuit protection device operates to clear the fault.

Four-wire systems are generally only installed on small merchant ships or passenger ships of any size, where use of phase voltage for equipment such as lighting and cabin supplies obviates the need for, and expense of, providing transformers. This saving is not, however, as great as it would first appear, as installation of the fourth wire makes cabling more labour-intensive. It should be further pointed out that some classification societies require the neutral to be earthed.

The argument for earthing the neutral is that if left insulated, overvoltages of 3.5 to 4.5 times normal voltage can occur under fault conditions and even because of switching surges. This subjects all equipment and associated cabling to high voltages. They are perhaps capable of withstanding such a high voltage once (for example during the 'high voltage withstand test' on completion of manufacture) but breakdowns could take place if such surges occur more than once.

Electromagnetic interference (EMI)

Mr Scott has only dealt with interference generated from within the ship's own system.

As is quite commonly known, a nuclear explosion produces an electromagnetic effect termed the electromagnetic pulse (EMP). It can damage electronic components (particularly SCRs) and can corrupt computer magnetic stores; it can also cause tripping of relays and insulation failures in cables. Its other effect is the change it makes to the electrical conductivity of the ionosphere and the atmosphere, causing havoc to radio communications and use of radar—nothing of course can be done about this.

If the information is not classified, would Mr Scott like to state what steps are taken in the electronic equipment associated with generation of electric propulsion and protection to alleviate damage from the EMP?

Cables

Having only recently had my first (albeit strictly limited) experience of low-toxicity cables, I am amazed by the number of people who think that the RN has only started to investigate their use because of the Falklands crisis, particularly with reference to loss of life on HMS *Sheffield*. As Mr Scott will confirm, the RN has been investigating low-toxicity cables for many years and has been using them for some time.

It seems that, to produce insulating and sheathing compounds which are of low toxicity on burning, rigidity of the material results. Mr Scott implies that low-toxicity, thin-walled insulated and sheathed cables can be used throughout the ship. I should have thought that their inherent properties make them suitable for wiring of switchboards and consoles but not for main runs, where chafing at supports would appear to be a grave risk. Would Mr Scott please clarify the areas in which thin-walled cables are used?

Although it is clearly shown that single-core cables have better current and weight properties than do cables in parallel, are the latter not very much more expensive? Also, by using either single- or three-core cables in parallel, difficulties arise in the formation of eddy currents with the former and terminations of the latter.

My last point concerns the training of personnel. As is stated in the paper, operation requires a high degree of skill. Since the introduction of EBD (Engineering Branch Development) in the RN, I believe that it is the Marine Engineering Division that operates the equipment, the Electrical Division being more concerned with equipment maintenance. Does Mr Scott see any problems with this way of thinking?

The opinions I have expressed are my own.

M. J. BOLTON (YARD Limited, Consulting Engineers): The author has produced a work of reference which will be valuable and useful to those in the Royal Corps, the RN and in industry who are concerned with warship electrical installation design. It would be even more valuable if the additional information presented by the author when reading the paper could be added as a supplement to the paper.

Figure 1 shows a 50% growth in load from the Statement of Naval Requirements to paying-off for a typical frigate. This appears to be about right for a vessel now paying off; would the author care to estimate what it should be for a ship whose naval requirements have just been stated and which would be expected to pay off in about 25 years time?

Figure 4 shows a mean load of 85% for a typical 1 MW generator set; what, roughly, was the average age of the vessels from which these data were recorded? Were they towards the end of useful life?

Referring to the column 'Parallel operation' in Table I, Item 4 suggests that there should be sufficient capacity to cater for throw-over load in the event of generator failure. Could Mr Scott explain what he intends here? If the generators which are running are connected in parallel and one of them fails, then what is the purpose of the throw-over arrangement? Perhaps it is intended that the system referred to may also run split? If not, why not shed non-essential services to bring the load down to that which can be supplied by the remaining paralleled generators?

Under Item 6 in the same column, it is stated that 'fault level is limited to the number of generators required for full load'. I find this a little worrying for several reasons. First, to change generators, one more than the number required for full load would need to be in parallel and it would be possible for a short-circuit to occur during the operation; indeed, short-circuits are probably just slightly more likely to occur during changes of system configuration than they are during steady state. Second, since all running load would also be in parallel, the fault contribution from it should be included. Third, if the load growth during life could increase by up to 50% of that designed, it may be necessary to run more generators in parallel than was originally envisaged, hence the specified fault level would have to include for this.

It would therefore seem preferable to calculate the busbar and feeder switchgear fault level as that which would result from all generators and all driven machines in parallel, unless there were means of positively interlocking circuit breakers so that this could not occur. Would the author care to comment on this?

Item 8 in the same column states that transient response is determined by the number of generators in parallel and this is generally agreed, with the proviso that it may be necessary, for example under emergency conditions in battle, to start a relatively large drive from only one generator.

On p. 6, the author refers to the RN practice of operating with the neutral point unearthed. A paper was read to this Institute last October upon marine neutral earthing and it was observed that it is sometimes the practice to use other arrangements, including a solidly earthed neutral. It is doubtful if many, if any, would support this for the main power supply system but it might have some merit for the 115 V circuits. If, instead of using individual single-phase transformers throughout for non-essential circuits, one used three-phase transformers with solidly earthed neutral, then distribution could be made from TP & N distribution units, thereby saving on cable and distribution gear.

Most earth faults would thereby be self-locating and this has already been proved to save labour in commercial ships. Under action damage conditions, under which multiple earth faults could occur, many would be automatically cut out by the protection fitted, thus making it easier to locate and rectify remaining earth leakages which did not operate protection but which were still a nuisance. It is perhaps time to reconsider the possibility of a change to 240 V for lighting, etc., with or without solidly earthed neutral. The saving in cabling and distribution gear would be considerable and, for non-essential and domestic services, standard shore-side equipment could be used. Again, there is a precedent in commercial ships and it has been successful. It is understood that 240 V was considered not so long ago for warships but at that time, probably quite rightly, it was not chosen for practical and standardization reasons.

Was Fig. 8 drawn for a split system? The diesel generator three-phase and phase-to-phase fault current characteristics are both shown as straight lines; why do they not follow the normal decrement pattern?

I am not completely familiar with the type of OVPU used in RN surface ships but from what is said in the paper it would operate for an overvoltage fault on all machines in parallel so that all would be tripped together. No doubt some means of discrimination is included; would Mr Scott explain how this operates?

Regarding EMI on p. 9, it is agreed likely that EMI levels will of necessity have to be lower in future but this may be avoided to some extent by signal conditioning. One solution which may be possible for adoption in the future concerns fibre optics, as it is understood that methods of terminating and repairing optical fibres are improving considerably.

F. M. PEARCE (Salplex Limited): The paper highlights the complexity of the electrical installation on a modern naval ship, noting that this is contained within a smaller volume than comparable land-based systems and operates in a highly demanding physical and electrical environment. The large number of connections quoted for typical vessels is particularly revealing, since it is difficult to maintain a high standard of reliability in electrical joints which are formed away from the controlled conditions of the factory floor; and it would thus be interesting to know to what extent their sheer volume on a fighting ship contributes to the overall system failure rate.

The author refers to the continuing trend towards greater complexity in shipboard electrical systems and may therefore agree that it is important that the technology used for interconnecting the various systems keeps pace with the development of the systems themselves.

Marine electrical systems present a unique range of requirements to the designer and, at first sight, the problems of power distribution on, for example, the modern passenger car appear to be very different. Nevertheless there are some striking parallels with the shipboard situation, e.g. space is at a premium, complexity is growing apace and the range of physical/electrical environmental conditions is both tough and wide; in both cases there is a demand for improved performance, reliability and 'testability'. In these circumstances, it is interesting to consider whether the general approach now being proposed for automotive electrical systems is relevant to shipboard applications, namely the use of multiplexed or electronic wiring systems for both control and power distribution networks.

The principle of multiplexing is not of course new but modern systems depend upon compact and highly reliable electronic units employing solid-state circuits; these are located at suitable geographical points on the network to accept inputs and outputs adjacent to them, for example in the manner illustrated by the elementary system shown in Fig. D1. Here, each power box (PB) is capable of accepting up to eight inputs and eight outputs; for automotive applications, it is contained in a diecast aluminium box, as in Fig. D2. Conventional wiring connects from the bottom of the box to the associated input and output devices; the power/signal cable is of coaxial construction and connected to the socket at the top of the box. For application at 12/24 V and currents up to 40 A, this robust cable is physically no larger than a domestic television cable.

Field experience to date has confirmed that a high standard of EMC performance is obtainable with such systems; if necessary this may be further extended by the substitution of a fibre-optic signalling channel for the copper signal wire.

Although current automotive designs are proving successful, it is not suggested that they are directly suitable for shipboard use. Nevertheless, the author's opinion on the value of this approach is invited.

CDR M. B. F. RANKEN (Aquamarine International Limited, London): This is an interesting and useful paper about perhaps the most vital system in every ship today, both naval and merchant. But electrical machinery has been, and perhaps still is, the cinderella of marine technology both in the RN and in the merchant service. Most engineers, other than electrical, are afraid of electricity and electrical training has often been inadequate; I suspect it still is for merchant service tickets.

Most electricians are more interested in the applications of electricity, rather than how it is generated and supplied; and ships' staffs prefer those applications to be outside the machinery spaces. The RN used to have the High Power Electrics (HPE) Section of the Engine Room Department to look after auxiliaries associated with main and auxiliary machinery; that section usually comprised a 'makey-learn' Engineer Officer, maybe a 5th Class Engine Room Artificer, and a couple of Leading Stokers or Stokers (now Engineering Mechanics). But the Torpedo Department was responsible for the whole electrical supply, distribution and application throughout the ship, other than the Engineers' HPE; most of this, especially the generators, ring main, switchboards and distribution boards, was looked after by a Warrant Electrician and a few Leading Torpedomen and Torpedomen, who could call on an Electrical Artificer when needed—most Torpedo Officers considered HPE as rather 'infra dig'! Later the Electrical Department was formed but, being staffed initially from Torpedo and Special Branch officers and men, its main interests were also in applications and electronics.

The design of electrical machinery and systems was the responsibility of the Director of Electrical Engineering and his Department. The driven units of auxiliary machinery came under the Engineer-in-Chief, the Directors of Naval Construction, Naval Ordnance and Underwater Weapons. Generator prime movers—turbines and diesel engines—came under the Engineer-in-Chief. There was little or no input of sea experience to the Electrical Engineering Department (DEE), and

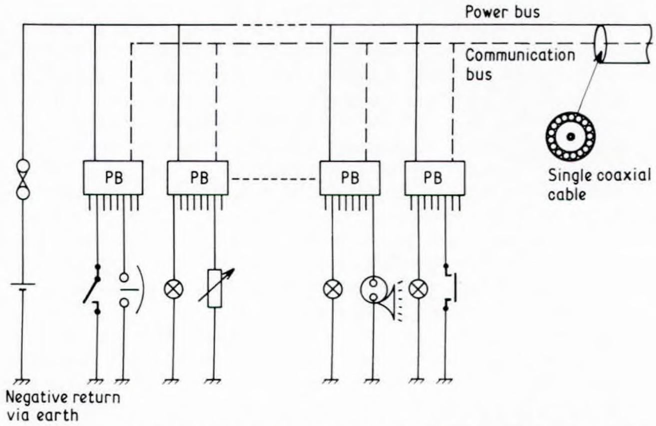

FIG. D1 A simple any-point to any-point multiplex power/control network

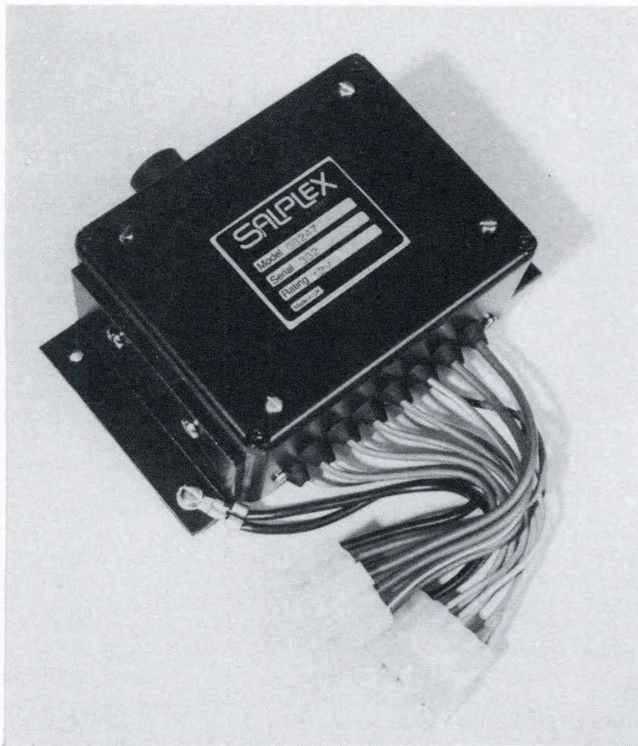

FIG. D2 Typical power box for automotive applications of multiplexing

thence to the manufacturers. Many d.c. motors, starters and control gears were quite inadequate for the conditions of ambient temperatures and humidities, even of powers absorbed in relation to designed maximum available; these required constant care, maintenance and frequent repair of commutators, bearings, brushes, contactor springs and contacts, and fuses, often involving makeshift replacements and dangerous wiring or gagging of safety devices.

It is gratifying that the main supply system is now the responsibility of the Mechanical Engineering Branch for maintenance and operation, as 'one of the propulsion or auxiliary control systems'. Where does the demarcation now lie operationally (see p. 11, 1st column, last sentence)? What steps are now taken to develop the feedback to the design authority (Ship Department) of sea experience, especially nowadays, when the number of serving officers is so much smaller than in the past, though they were non-existent in the old Electrical Engineering Department?

The Admiralty eventually adopted the land telegraph in 1849; by 1861 there were 11 000 miles of submarine cables (but only 3000 miles of them worked!). The invention of the Whitehead 'locomotive torpedo' led to the 1873 Torpedo Committee looking for defensive measures. At that time electricity was used only for firing circuits—guns, spar torpedoes and mines; very low power, low voltage and hence possible with primary batteries.

But the Torpedo Committee wanted 'searchlights' (their choice of words) of greater range than the torpedoes of the day (then about 800 yards) to enable attacking torpedo boats to be located and hopefully stopped or avoided before they could fire their torpedoes. These first searchlights were 22 in diameter, with a lens-concentrated beam 3–4 deg wide, with a range of half to one mile; they required 'high' voltage, high power for their carbon arcs. Therefore initially six hp Wilde steam-driven alternators were fitted to give 11 000 candlepower. In 1880 Gramme d.c. generators were introduced, as they gave better control of the brush low-intensity carbon arcs. Was this first application of electric power the reason why the RN adopted direct current for the next 65 years, and also why responsibility for electricity became part of that of the new Torpedo Department?

The so-called central citadel type battleship *Inflexible* of 12 000 tons had four 16-in guns and various smaller calibres; she was the largest vessel so far built, and a highly controversial design, which led to her being described as an ugly hybrid. Her first Captain was 'Jackie' Fisher, already the great reformer of the Navy, who had founded the Torpedo Department and HMS *Vernon*, the Torpedo School. He demanded from the Admiral Superintendent at Portsmouth, where she was built, a navigating bridge, more water closets and incandescent lamps; the first and second were considered 'unnecessary', the last 'dangerous'! But he nevertheless got all of them. Carbon filament lamps were invented in 1879 and the first major installation seems to have been in the *Collosus* of the same class, one of the first two all-steel ships in the Navy, completed in 1886; she had 264 lamps, three searchlights and three Gramme dynamos, all on 60 V d.c.

Inflexible was designed by Sir Nathaniel Barnaby (1829–1915), the first Director of Naval Construction and the first Head of the Royal Corps of Naval Constructors, the centenary of which fell in August 1983; he was also a founder member of the RINA in 1860. Barnaby accompanied Jackie Fisher to the Mediterranean and they 'hit an awful gale in the Bay of Biscay. Sir Nathaniel nearly died with seasickness. I was cheering him up, and he whispered in reply: "Fools build houses for wise men to live in. Wise men build ships for fools to go in".'

Although the French, German and US navies used a lot of electric motors, the RN preferred steam and hydraulic. The Committee on Electrical Equipment in 1902 outlined the many advantages of an all-embracing electrical system: less wear and tear than reciprocating machinery; no hot steam pipes in living spaces and no danger from steam leaks; it is easier to run electric cables behind armour and make watertight joints at bulkheads; auxiliary machinery could be run by power from shore or another ship, during refit or following damage. The only disadvantage was that electric motors would not run underwater, as steam and hydraulic machinery could be made to do. They recommended a great increase in electrics, including the working of the guns; an increase in voltage from 100 V (by 1900) to 200–230 V; a ring-main distribution system and the introduction of steam turbo-generators.

HMS *Ajax* in 1912 had two turbo and one reciprocating 200 kW generators (but the USS *Arkansas* had four 300 kW turbo-generators). In 1916/17 the USS *California* class battleship had turbo-electric propulsion using two 18 500 hp turbo-alternators and four motors, one for each shaft, all at 3400 V; all the guns, ammunition hoists, capstans, pumps and steering gear were electric, fed from four 300 kW turbo-generators. Advantages claimed for the propulsion system included flexibility in design; better underwater protection; much shorter shafts than for steam turbines; turbo-alternators amidships with the boilers outboard; all units were in separate watertight compartments; weight and space the same as for steam turbines, and at cruising speed only one turbo-alternator required, making the system more economical; the propellers did not race if they came out of the water in a seaway. 'The US Navy kindly supplied the British Admiralty with full particulars . . . but the principle was not followed in the Royal Navy.' (p. 154, *The Electron and Sea Power* by Vice-Admiral Sir Arthur Hezlet, Peter Davies, 1975).

Post-Jutland, HMS *Hood* had eight 200 kW generators, four reciprocating and two each turbo and diesel; she also had the first metal-filament electric light bulbs, which were much more shock-resistant, and a wide range of auxiliaries, pumps, fans, winches, lifts and small machines motor-driven. But the *Nelson* and *Rodney* with six 300 kW generators had only 200 kW more than the *Hood* when completed in 1927. In the same year the US aircraft carriers *Lexington* and *Saratoga* had 209 000 hp turbo-electric propulsion on four shafts, each with two 22 500 hp motors, the whole controlled from a central position. The US Navy also had diesel-electric propulsion in their 1936 fleet submarines, 6400 hp giving a speed of 20 knots, from four generators feeding two shafts. But battery development had not progressed far beyond the endurance obtainable at the end of the First World War.

In contrast, much energy was expended in the RN in developing large 36-in and 44-in diameter searchlights of longer range right up to 1939. They 'would have been splendid at Jutland but by the time they were in service night fighting had moved into an entirely new era' (ibid. p. 168).

As in every other field of technology, 'we went into the Second World War still largely with the weapons and machinery and tactics of the First.' (Vice-Admiral Sir Louis Le Bailly, 'The One Open Highway', Leeds Castle Conference Towards a Grand Strategy for Global Freedom, Foreign Affairs Publishing Co. Ltd, Richmond, Surrey, 1981.)

We had considerable experience of US machinery and electrics during the War, mainly in escorts and escort carriers, and in merchant ships. Most of this was more advanced and better than our own. 440 V, three-phase, 60 Hz was already standard throughout the US Navy. It was natural for our *Daring* class destroyers to adopt this supply in 1946, as we were using numerous equipments and systems common to both navies. Some tankers followed suit, including US-built wartime vessels, but most merchant ships stayed on d.c. at that time; then later several went to 50 Hz a.c. supplies, to correspond with the shore supplies available at their normal ports of call in Africa, India, Australia and elsewhere; it is noteworthy that 40 and even 30 Hz were still in use in some Caribbean islands up to 25 years ago.

The Royal Mail Line's 20 000 grt passenger/chilled meat liners *Amazon*, *Arlanza* and *Aragon* went to 440/3/60 a.c. supplies around 1959 and this design is fully described in A. N. Savage's two papers to this Institute, 'Developments in marine electrical installations with particular reference to A.C. supply' (May 1957) and 'Details and operating data of recent A.C. installations' (May 1961). The connected load in these ships was 6108 kVA, of which 41% was for refrigeration and air-conditioning. These papers merit comparison with the present one, both as regards the philosophy of those large installations and the advances that have been made since.

Diesel submarines (SSKs) now remain the only vessels which must retain d.c.; and there is less and less d.c. experience on which to build the next generation in today's manufacturing industry.

Apart from the *Fearless* class, the aborted CVA-01 and, much later, the *Invincible* class, all designs of surface ship over the past 25 years have been essentially 'small' ships. But today's 'small' ships have major warships' electrical loads: though why is not always clear, taking into account modern developments in electronics, computer technology, the 'chip' and the rest. Has the philosophy of the 'small ship' layout been discarded in working out damage control arrangements and providing alternative power and other supplies as far as possible? The old concept of the 'expendable' small ship is no longer acceptable, even although a single modern missile can presumably sink it, if it goes off, quite apart from the fire damage which did so in the Falklands campaign. Those fires should have been extinguishable, or at least containable within one section of each of the ships concerned.

Economy of operation is wanted over the widest range of electrical loads. Similarly, optimum generator loads are about 80–85% of full load, especially with diesel prime movers. Naval experience with these has never been very happy, and in the days of steam the minimum use was made of the diesels, which may have aggravated the situation since they ran a great deal on light loads, with the main load on the turbo-generators. Merchant ships usually have fairly constant load patterns at sea, for which generator sizes can be optimized to achieve efficient running, though harbour running can be on very light loads, but nowadays seldom for extended periods; some classes do have heavy loads while embarking and discharging cargo. Many of these ships use shaft generators at sea, to permit the diesel-generators to be stopped; some have turbo-generators using waste-heat boilers in the main diesel uptakes.

Warships do of course have to cater for a wide range of loads and conditions from routine running at sea to action stations with much standby power, to emergency operation and finally to re-establishing power following damage. This tends to rule out some ideas common in commercial vessels, though one wonders whether all of them have been properly analysed before doing so. Parallelling of alternators seems to be again under consideration, a condition for which several reliable control systems have been installed in various types of merchant ship. With the wide range of loads experienced in warships, and the great importance of minimizing maintenance by optimum running of diesel prime movers, there is obviously a considerable juggling act involved in selecting the optimum numbers and sizes of generators, both main and emergency, and the distribution system(s) to connect them economically and also under all the other operational conditions to the various essential and other connected loads. Have gas turbines been considered, in the light of long experience with these in the offshore industry for power generation, as well as in the Middle East, for both power and fresh water production?

The thyristor converter system from a.c. to d.c. propulsion motors for the Type 23 frigate design does seem to introduce a lot of problems, as described in the presentation of the paper. Efficiency must be lost in the conversion, quite apart from the EMI and distortion caused. The reasoning behind this choice would be interesting, observing that various electric propulsion systems have been used over the years in small as well as large ships, some of them involving a lot of manoeuvring and slow-speed running; these have been both d.c. and a.c., and several were in British ships.

It is very desirable to get away from unnecessary multiple voltages and frequencies. 'Total system design' is obviously a great help here, rather than just treating the electrical system as the humble servant to which each outlet can dictate its own pet requirement, which is convenient but not necessarily essential or economical, quite apart from the distortions and interference which it may introduce.

Could something be said about power factor control and starting current limitation? The 5 kVA limitation mentioned is similar to typical public utilities' regulations requiring star/delta or incremental starting on motors over 7.5 hp. Is static switching employed to any extent and, if so, on what types and sizes of loads?

Cable runs should be sited as far apart as possible for alternative supplies. Is any armoured cable used nowadays, which would be resistant to fire as well as to damage? Alternatively, have cable trunks been used for main runs fore and aft, like the fire control and vital cable runs which used to be standard in bridge superstructures to connect the conning and command positions to transmitting stations and lower conning tower (steering position)? Of course these solutions involve extra weight, but hull forms and weight-carrying capacity can nowadays be provided without going to larger ships, as appeared to be the substance of the contribution read by Dr P. J. Gates.

Has any attempt been made to provide motors and generators which are watertight and can continue running in flooded compartments after action or other damage? Has the same been attempted for switch and control gear, or is this as far as possible installed high in the ship?

Mr Pearce suggested the use of harnesses such as are nowadays common on road vehicles, and generally reliable, with moulded connectors at either end. It must be said that equipment designed for heavy lorries never worked in ships' boats in the presence of sea water and the normal usage of able-bodied seamen; they simply were not 'Jack-proof'! Almost all the problems were with the connections themselves, though of course many control and relay boxes were not properly watertight, and so corrosion of contacts and operating springs soon put some of the units out of action, particularly on battery-charging and starter circuits.

H. RUSH (BP Shipping Limited): I found the paper both interesting and an illuminating insight to the fashion in which the MOD approach their electrical system design. The scope for questions seems almost endless, but I shall restrict myself to some general points.

Figure 1 shows a 25% growth of the connected electrical load between the 'Naval requirements', which I take to be the initial design concept, and the first commissioning. I can readily appreciate that the subsequent increase occurring during the ship's life will, for an RN ship, be extraordinary by comparison with normal merchant ships. On the other hand, it would be of interest to learn what particular difficulties face the designers, which preclude a more accurate initial assessment of the connected load. I noted during the authors' presentation his reference to data-logging; but, while this may ensure in the future a more accurate assessment of diversity factors and load factors, it will not improve the estimation of connected load.

The section on 'Main Supply Systems Arrangement' contains a statement that generators and switchboards should be above the level of flooding. I note that Fig. 5 diagrammatically depicts all the generators and switchboards below the waterline. Clearly the principles of engineering compromise have been applied. More seriously, for such critical elements would the author comment on the priorities which are allowed to dictate a compromise solution as against the preferred siting?

In Fig. 6 the essential load is shown fed from separate supplies but through a single changeover switch. While this is an arrangement commonly adopted to allow 'secure' supply for steering gear on merchant ships, I would hardly have thought it to be adequate for RN ships. A hit damaging the changeover switch would surely render both supplies useless.

A number of references suggest that high prospective fault levels give rise to problems in obtaining suitable equipment. Yet, as I understand it from the paper, previous practice has been to operate each generator singly on to its own board. It does not seem, from the generator capacities quoted in the examples, that fault levels are of such a value as would cause any heart-searching to merchant ship designers. Can the author quote typical levels which apply, and the reasons why equipment manufacturers may have difficulty? It is always difficult to cite 'typical' cases, but equipment for merchant ships is readily available at 440 V in the ranges for: air circuit breakers 80 kA breaking and 176 kA making; and MCCBs 180 kA breaking and 415 kA making.

In a similar vein, there is a comment in the paper that the generator sub-transient reactance is sometimes determined by the capability of the switchboards to handle the fault current. This machine parameter has a significant effect on the load acceptance/voltage response of the generator. How does the author see the priority when considering the Type 23 design of electrical propulsion, where the ability of the generator to start motors is more important—particularly if damage has occurred to some generator sets?

Still on the protection theme, I noted a number of references to the use of fuses, either as back-up to MCCBs or for distribution to circuits of less than 30 A rating. Considering the importance of maintaining systems and particularly restoring circuits quickly on a modern warship, does the author not think that a greater use of MCCBs and miniature MCCBs should be made? This would reduce the opportunities for failures in supply due to fuse fatigue, and would enable much faster restoration by switching actions rather than fuse changing.

If fuses are preferred, then what is the fusing factor which would normally be specified? (By fusing factor we mean: the rated minimum fusing current (4 hours) divided by the circuit current rating.)

If, as is stated, 45% of cables are sized on voltage drop, one wonders why the relatively low voltages (and thus higher currents) are used for supplies to such items as lighting and small power sockets. European merchant shipping practice would be to use 240/220 V. It would also be interesting to know what voltage is allocated to portable tools. DoT guidelines restrict us to a maximum of 30 V to earth for safe working practice in wet/damp areas.

If I may also add a comment on the contribution from Mr Bolton to the discussion, I would briefly refer to his suggestion that an earthed neutral system holds advantages in aiding earth fault location. While I do not dispute this point at face value, we have recently conducted a survey in our fleet over a period of 3 months. The results have yet to be analysed in detail but for all systems the initial indications are that an average of 3 manhours per month per ship is all that is spent in tracing earth faults. Our fleet is well maintained and these data may not be representative of the industry generally. Could one justify a change from unearthed systems on this basis?

B. KITCHEN (Vosper Thornycroft (UK) Limited): The distribution schemes described include a large number of fuses, not only for downstream distribution but also for circuit breaker protection. I am sure Mr Scott would agree that fuses are less desirable in a warship application than breakers, particularly in the case of reconnecting circuits after faults.

It is significant that discriminating fault-limiting breakers are not mentioned, which would eliminate the majority, if not all, of the fuses in the distribution scheme discussed. The environmental conditions, particularly shock, prohibit the use of such devices until developed in a shockproof form.

This is just one example of the severe restrictions placed on the choice of systems and equipment for warships, and I wonder why Mr Scott did not take this opportunity of explaining the magnitude of this problem?

Author's Reply

I thank Dr Gates for opening the discussion and for his comments on the paper.

The comments on weight savings are noted but cannot be supported. The weight savings obtained from the use of LFH cables can be very significant in new-design ships as well as for ships that are undergoing modernization. The new US *Aegis* class cruiser, for example, has had to be designed using LFH cables to enable the desired stability criteria to be met. The significant factor is that the majority of these new cables are, at present, used in weapons control and communication applications and are therefore sited high in the ship with a significant proportion of the cabling in the superstructure. Weight savings here do have a significant effect on ship stability. We therefore conclude that weight savings are invaluable.

The electrical transmission characteristics, including EMC performance, of the LFH cables are currently under detailed investigation. As Dr Gates correctly states, because of the changes of insulation material and a reduction of thickness, differences in electrical characteristics between the new-technology cables and existing types are experienced. At the time of writing, comparative testing is being carried out on samples of both multi-core and twisted-pair cables.

In the case of multi-core cables, EPR or silicon rubber insulated cables are expected to have a slightly lower capacitance than the new LFH cables, but not significantly lower. However, the capacitance is expected to be considerably lower than existing PVC insulated types. Multi-core cables are generally only used at low frequencies, typically d.c. to 10 kHz, and thus no EMC problems are anticipated with the new cable; and with electrical performance generally similar or improved when compared to existing cable types.

In the case of twisted-pair cables, the capacitance depends upon physical dimensions, the dielectric used and screening. In general the new LFH cables have, in the case of silicon rubber or EPR, higher capacitance, in the order of 20–40% when compared to existing types. The capacitance of the new cable is, however, expected to be up to 80% lower than the PVC equivalent. At frequencies below 1 MHz, therefore, the EMC and cross-talk problems of twisted-pair LFH cables are not expected to be significant.

The major problem experienced in trying to maintain supplies of the required quality (Defence Standard 61–5) is in trying to minimize the effect of waveform distortion. The problem is acute on a shipborne system, as one is operating upon a finite busbar system with a high proportion of the load being rectified supplies to high-powered equipments.

Harmonic conditions in a power system can be made worse by capacitors and RLC effects of cables which can give rise to resonant conditions which in turn amplify the harmonic currents and voltages. The distortion of the waveform can cause interference effects in communication circuits and interfere with the operation of devices and equipments, particularly those that depend upon a sinusoidal waveform for correct operation, e.g. a point on wave control system.

Harmonic currents, besides being a source of power system interference, also have other detrimental effects such as lowering the power supply input power factor, reducing motor efficiencies and causing increased heating and commutation problems in rotating machinery.

It is for the above reasons that NES 532 Section 6.8 applies limits on the acceptable level of harmonic distortion on a shipborne power system. Levels of 5% THD and 3% individual harmonic content are the accepted values for ships' 440 V, 60 Hz systems.

The restrictions placed on the equipment designer are intended to limit the total voltage distortion to 3% and keep the individual harmonic content below 1.5% at the equipment terminals, so that the additive effect of a number of loads will not exceed the quoted system limits. Obviously, as the constraints have been placed in relation to the voltage waveform distortion, the latter will be related to the equipment's harmonic current demand and the source impedance. The latter will vary with generator and distribution system capacity and ship loading state, but these have to be specified so that an equipment designer knowing the harmonic current demand can calculate the consequent voltage distortion. The design of equipment taking from the supply is based upon the assumption that the supply voltage waveform will be within the limits of Defence Standard 61–5.

The design of rectifying and all other non-linear waveform equipment of 20 kVA and above is carefully scrutinized by DG Ships so that distortion effects can be minimized. Measures taken to limit distortion include increasing the pulse number of rectifiers; thyristor controllers should employ 'burst firing' rather than 'phase angle' control, and transformer isolation should be provided wherever possible. In general, provided the distorting load on a system is less than 10% of the total load, then problems do not arise.

Miscellaneous other guidelines are imposed on equipment manufacturers to help maintain the quality of the electrical supply to within Defence Standard 61–5 limits. For example, in order to prevent voltage unbalance, all loads of 5 kVA or greater should operate from the main 3-phase, 440 V, 60 Hz supply and the difference between the highest and lowest line currents under normal operating conditions should not exceed 5% of the arithmetic sum of all three line currents.

In order to prevent modulation, modulating loads should be limited to below 5 kVA. The maximum permissible modulating power loading of a generator is 12.5% of generator loading and should not produce frequency modulation greater than 0.5%. This is calculated as one-half the difference between the maximum and minimum frequency expressed as a percentage of nominal system frequency.

Finally, limits are placed on the starting currents of motors and in the inrush currents to transformers. The allowable values are defined in detail in NES 532 and NES 632.

In response to Mr Robinson's comments on load analysis, a major contributing factor to light engine loadings in the past has been due to overestimation on the part of the power consumer. It will be appreciated that, in order to prevent obsolescence, equipments are often designed in parallel with the main electrical power system, which makes an early accurate assessment of an equipment loading very difficult. The tendency has been for users to err on the cautious side and overestimate equipment power consumption, which has subsequently led to the light loading problem. Growth margins in recent years have been reduced mainly as a result of a change in policy. Current ships are no longer designed to have a mid-life refit but are now replaced at the end of their useful operational life.

No use is made of the transfer of refurbished generator sets between vessels. As the author will be aware, there are many other factors to be considered, such as fault levels, cabling, switchgear changes and protection. The approach suggested, therefore, would not prove to be cost-effective.

Internal studies have consistently shown that it is not cost-effective to use waste heat exchangers as a means of improving overall efficiency. This is primarily due to high costs of pipework and the difficulty in running such pipework into the very congested areas found in RN vessels.

On the subject of generator ratings, the data-logging system used on first-of-class ships has shown that the power factor of the main electrical power system has remained fairly constant in the range 0.8 to 0.9. This of course will not be true for the Type 23, where the power factor will be determined to a very large extent by the thyristor-controlled motor load.

As Mr Robinson will be aware, the design of the electrical distribution system is one of engineering compromise, with the chosen sub-transient reactance giving tolerable fault levels as well as acceptable transient voltage performance. In the case of the Type 23, for example, the sub-transient reactance, whilst limiting the fault levels to within the capabilities of the switchgear, will still allow the largest motor load to start directly on-line with only one diesel generator set running. With regard to motor starting, potential problem areas are run on a computer simulation model, which will highlight whether any adjustment is required to the starting or control gear mechanisms.

With regard to distribution, although MCCBs of 51 MVA are readily available, none were found to meet the required RN shock standards.

Local motor control centres for EDCs have been investigated in the past but have been rejected on the grounds of increased cost (far longer cable runs for starter protective devices) and greatly increased vulnerability.

The protection being considered for use on the Type 23 is as follows:

(a) Differential.

(b) Full current/time discrimination on all circuit breakers.
(c) Reverse power.
(d) Excitation protection.

In the case of a generator AVR failing to full output, the excitation protection fitted in the Type 23 will detect the faulty AVR and will trip the associated supply breaker. Time discrimination will prevent the healthy generator from tripping on the reactive circulating overcurrent. In the case of only two machines running in parallel, then the remaining generator is capable of supplying all the essential load.

It is common practice in RN ships to fit an inhibit circuit into the AVR, which, at 80% underspeed, will inhibit the AVR output voltage. The generator will eventually trip on undervoltage.

The load-shedding arrangements to be fitted on the Type 23 have yet to be finalized. However, the most likely operation is that the automatic load shedding will be carried out by tripping selected EDCs. These EDCs will, of course, only supply non-essential loads.

In response to comments on quality of supply, the waveform distortion problem is particularly acute in RN vessels due to the high density of sensitive equipments (e.g. radars and sonar transmitters). Rigorous EMC specifications are applied to all equipment and this alone supports our tight voltage waveform specification.

In designing the Type 23 electrical system, both motor generator sets and transformers were investigated to supply the 440 V distribution system. The criterion that necessitated the use of motor generator sets was that of waveform distortion. The 440 V distribution system has to operate within Defence Standard 61–5 limits and only motor generator sets enabled this specification to be met. Transformers would also have created an EMI problem and therefore were discarded.

On the subject of EMI, the MOD are not at present considering the use of fibre optics for use in the Type 23. There are still doubts within the MOD about the long-term reliability of fibre optics under adverse conditions and also problems of making connections after cables have sustained action damage.

With regard to cables, although there is a high proportion of non-power cabling in a warship, the cable runs tend to be short; thus the savings in cable cost offered by multiplexing are not as large as might seem at first sight. There are positive advantages to be gained by the use of multiplex techniques and these are the subject of study. It must also be recognized that the equipments fitted in a modern warship can be up to 20 years old and thus the cost of interfacing to a ship-wide ring-main multiplex system is prohibitive.

It is noted that PVC cables with a maximum conductor temperature of 75°C are available. PVC cables are very limited in RN ships and tend to make up only about 5% of the total application.

It is agreed that the cost of LFH cables is at present higher than that of conventional cables but it is expected that, when large-scale production of LFH cables is achieved, the cost differential will disappear. The increase in installation time and labour costs is, we believe, due in the main to having to learn new work practices. When LFH cable is more widely used and work practices become established, their benefits will outweigh the minimal increase in labour costs.

Typically, in previous ships, a total of 20 V drop was allowed from the remote switchboard to the load via the interconnector cable, local switchboard, EDC and local fuse panel. Figure 12 in the paper was derived on this basis, which accounts for the high proportion of cables sized by voltage drop considerations. More recently, the regulations regarding volt drop have been relaxed and the situation still further eased by decreasing the quadature group allowed on the generator.

Mr Chilman commented on estimating load. Royal Navy ships do not have bulkheads similar to A and B class bulkheads as fitted to merchant ships. All current designs (with the exception of GRP vessels) have all-steel bulkheads which are coated in a fire-retardant paint.

Cable glands are commonly filled, however, with a setting (Dowcorning 9161) compound which has a half-hour at 900°C (from a radiant panel) survival. With such glands, problems may be experienced if, in future, additional cables have to be inserted (unless this is anticipated and blanks are fitted at the time of the initial installation).

On the method of operating generators in the ship's main supply scheme; in the cruising operational state, when action is possible, or in the hazardous conditions, such as docking or undocking, it is permissible to run in a two-generator configuration provided:

(a) The two generators can take the total load of the ship;
(b) Either generator can take its own load plus the automatic change-over switch (ACOS) throw-over load from the other without overloading;
(c) A third generator is standing by and, in the event of a blackout, can be started and the system rearranged if necessary in time to prevent the ship being hazarded;
(d) The two running machines are not paralleled for load transfer without first running up a third machine.

As an additional safeguard, a preferred arrangement is for the running generator to be in a separate compartment.

In the case of a split-run electrical power system, failure of one generator set will result in the supply to an item of essential equipment that is fed from the ACOS having supplies restored in 0.1–3.0 seconds depending upon the ACOS setting. Equipments that cannot tolerate any break in supply have to have a battery back-up system or be dual-fed. Non-essential loads would be fed from a standby generator set which could take up to one minute to get connected on to the switchboard. In the latter case, some motor loads would have to be restarted manually, as the starter would have tripped on undervoltage release.

Regarding the method of power distribution, it is accepted that if the neutral of a distribution system is left insulated then overvoltages of 3.5 to 4 times normal voltage can occur during fault and load-switching conditions. In order to cater for this, all RN equipments are subjected to and have to withstand (for 440 V supplies) spike injection tests of 2500 V. In general, the advantages of the isolated neutral system, as listed below, far outweigh any of the disadvantages:

(a) An earth fault can occur on an essential service without causing loss of supply to that service;
(b) The otherwise adverse effects of no zero-sequence impedance of the generators on the fault capacity of the switchgear is avoided;
(c) With no neutral connection, neutral switching and circulating currents are avoided;
(d) Earth fault protection costs are low;
(e) Fire and flash hazards are low;
(f) Small, isolated, unearthed low-voltage sub-systems can be inherently safe, since the potential earth fault current can be restricted to less than the lethal level.

Security implications prevent the release of detailed information on the subject of EMP protection as applied to equipments. As a general philosophy, however, platform hardening as opposed to equipment hardening is applied wherever possible, i.e. effectively making the ship as a whole EMP-tight. If this aim is achieved, then EMP levels inside the ship are reduced to levels that do not cause permanent damage or equipment malfunction. Examples of the measures taken to achieve this aim are as follows:

(a) Minimize exposed number and length of cables;
(b) Screen those cables that have to be exposed.

As a general rule, if sound EMI practices are followed then the ship will have a good EMP performance.

On the subject of cables, it is confirmed that investigations into the use of LFH cables have been progressing since 1976, particularly with regard to their flammability and the release of toxic substances, notably hydrochloric acid gas. It is true that LFH cables tend to be rigid but some confusion appears to have arisen in the cable construction. In the main, the rigid material referred to is the conductor insulation. The outer sheath of the cable still conforms to NES 518 and therefore the problem of chafing at supports does not arise. A rationalized range of cables up to 2.5 mm^2 has been produced (80% of the ship fit) and it is intended that this will be used in all future applications.

With regard to single versus parallel running of cables, the relative merits of each individual case have to be judged on grounds of performance, cost, weight and volume. It is agreed that careful design and routeing of cables has to be undertaken in order to prevent eddy current formation and EMI problems.

With the advent of EBD, care has to be taken to ensure that equipment is user-friendly and is operable by an individual with relatively little electrical engineering skill. This, together with reduced manning levels, has necessitated the greater automation of plant. This will hopefully increase integrity of supply by reducing the incidence of operator error and provide sufficient information at the right place to give anticipation of plant failure in order to replace it without interruption of supply.

I thank Mr Bolton for his comments on the paper. The additional comments that I made at the presentation of my paper have been added as a supplement.

With regard to the specific questions raised, Mr Bolton asked for an estimate of growth in load between the Statement of Naval Requirements to paying off. As outlined in the presentation, we are being much more critical in our load estimation and are also obtaining better data from sea as to the actual diversity and utilization factors. This allows a more accurate assessment of the power requirements to be made and thus a main electric power supply system that is more closely matched to the load. I would estimate that the combination of these factors means that the increase in load for a ship being designed now, which would pay off in 25 years time, would be in the order of 10–15%. A great deal depends upon whether the 'repair by replacement' policy as applied to the ship is continued. In such circumstances no major mid-life refit takes place so that, theoretically, a growth margin for a current ship need only be small.

With regard to Fig. 4, this figure is slightly misleading in that it was developed from data gathered from a ship during the period of her first-of-class trials. On the basis of 'current' data-logging information, the curve is deemed to be appropriate to a vessel towards the end of its useful life.

Referring to Item 4 in the column 'Parallel Operation' in Table I, a term has been adopted which, as Mr Bolton points out, is more appropriate to split systems than parallel systems. The point is that there must be sufficient capacity in the system to take the load in the event of a generator set failing. If two generators are running in parallel then they must not be loaded to greater than 50% each; if three are running then each must not be loaded to greater than 66%. It is not intended for a system designed for parallel operation to be run split and, if there is a potential overload, we would do as Mr Bolton suggests and shed non-essential loads. The load-shed philosophy is indeed being adopted for the current Type 23 design.

With reference to Table I, Item 6, it is stated that 'the fault level is limited to the number of generators required for full load'. This is indeed the case for a parallel system in a steady state and not in a transient state, i.e. not undergoing load or generator transfers. It is agreed that the maximum fault level that can occur on the system is when all the generators are running in parallel, that load contributions to the fault level should be included and that the switchgear be rated on this basis. This was the philosophy behind the fault level calculations for the Type 23 design.

Present policy does not allow for growth margins in the order of 50% and it is not envisaged in any of our current designs that it will be necessary to run more generators in parallel than was originally intended, or even to increase the ratings of the initial generator fit.

In early studies of the Type 23 design the option of positively interlocking circuit breakers was considered in order to reduce the fault levels. It was found to be unnecessary to adopt this approach, however, as, by specifying a sub-transient reactance minimum figure, an engineering compromise was reached that limited fault levels to a tolerable level as well as giving acceptable transient voltage performance/load acceptance of the main electrical power system. In this instance it is still possible to start the largest motor load direct on line with only one diesel generator set running.

It is agreed that if 115 V circuits were supplied, as Mr Bolton suggests, by earthing the neutral, some savings would be made on cable and distribution gear. The biggest disadvantage of this method for RN vessels, however, when compared to the isolated neutral system, is that even on non-essential circuits it is desirable to have the choice of whether or not to tolerate a single earth fault rather than have the service automatically cut out by the protection. The protection on the isolated neutral system would not operate unless a further earth fault occurred on the same non-essential service.

Self-locating earth faults on the 115 V non-essential service would not aid earth fault detection on a 440 V main supply system, as the 440 to 115 V transformer would provide complete electrical isolation between the two.

As Mr Bolton rightly states, 240 V is not used for lighting as it is a non-standard voltage as far as NATO warships are concerned. The cost of developing a new range of 240 V, environmentally tested lighting and distribution equipment would also be considerable.

The discrimination diagram shown in Fig. 8 is drawn for a split system. It is not obvious from the figure but the three-phase and phase-to-phase characteristics referred to are, in fact, thermal limits for the generator. The normal decremental pattern limits approximate to straight lines when drawn on log-log axes.

The OVPU used in current surface ships is not designed to run on parallel operated main supply systems. In the case of a fully parallel run system, discrimination would be applied in order to prevent all of the machines tripping together on an overvoltage fault. The most likely cause of a sustained overvoltage is a faulty AVR failing to full output, in which case discriminatory excitation protection would trip the appropriate supply breaker.

Fibre optic cables are not being considered for use on current design ships, mainly as a result of the problems of repair and termination. The problems of repairing optical fibre cables after sustaining action damage are particularly acute. In the longer term when these problems are resolved then their use will have many benefits, particularly with regard to EMI.

I thank Mr Pearce for his comments on the paper. As he rightly states, the number of connections in a system must influence the system failure rate. Unfortunately, despite efforts on this particular topic we were unable to find any conclusive data that would enable an accurate determination of system failure rate to be made from the failure of cable connections. Experience has shown, however, that once a system is commissioned the number of failures due to connections and terminations is minimal.

The use of multiplexing techniques on conventional warships has to be considered in relation to cost, installation and weight. In a ship of frigate/destroyer size, approximately 40% of all cables are high power and another 15% are of such a nature as to preclude multiplexing, e.g. RF coaxial cables and weapon-firing circuits. This leaves a theoretical 45% of all main-run cables as potential candidates for replacement by a smaller number of multiplexed cables. If multiplexing could be applied on a whole-ship basis, then savings in weight and number in the order of 25% might be made. The amount of local wiring would of course be unaffected.

The difficulty in applying multiplexing techniques to ships' systems is that most are widely distributed throughout the ship rather than concentrated in a few 'geographical' areas. For most of these systems, therefore, there is little scope for multiplexing as only a few common paths exist, i.e. 'tree' rather than 'point-to-point' networks.

If multiplexing were applied to, say, the main electrical power control system for example, and the necessary equipment were fitted within each breaker cubicle and the primary control panel, then it is estimated that an installation labour saving of the order of 900 hours and a weight saving of 250 kg would arise. However, it is estimated that when the additional cost of the multiplexing equipment to RN standards is taken into account, then the nett cost of the ship would increase by £150 000.

The most promising method in applying multiplexing techniques to a warship design is by the 'data highway' approach which would be common to all systems. Studies have again shown, however, that any labour savings in this approach would be cancelled out by the increased work required for local connections (the method would approximately double the number of electrical connections to be made by shipyard labour as compared to point-to-point wiring). There would be a saving of some 25% in weight and space of main-run cables but, again, this would be cancelled (especially in the case of the new LFH cables) by the extra space and weight required in compartments to accommodate the multiplex units. Finally, therefore, we are left with material costs and, in our opinion, additional complex electronic equipment is likely to exceed the saving in cable costs by a factor of five.

The broad conclusion is, therefore, that any policy to adopt multiplexing in ships of the future cannot really be justified on cost, weight or space grounds. This is not to say that multiplexing should not be used where it fits naturally into the system technology and it is already used in existing ships for such things as digital data transmission to operation room displays and machinery surveillance systems.

I thank Cdr Ranken for his comments on the paper. In response to his question on EBD, the Marine Engineering Officer is responsible for the generation and distribution of electrical power including lighting. Equipment and systems responsibilities in ships and submarines are allocated to the ME department when they are clearly part of the 'float' or 'move' function and to the WE department when they are clearly part of the 'fight' function. When an equipment or system provides a common service, maintenance responsibility for the whole system falls to the department (ME or WE) which is the major user or to whose function most of the sub-systems subscribe.

The line of demarcation between a common service and equipment connection to the service is at the point of isolation of the equipment in question. In the case of mechanical systems, it is at the joint on the equipment side of the valves which isolate the equipment. In the case of electrical equipment, it is to be on the supply side of the isolating switch, MCCB panel, fuse or distribution panel dedicated to a WE equipment. Where this isolating equipment is used for both ME and WE equipment it is an ME responsibility. Automatic, hand and emergency changeover switches on the main electrical distribution system are the maintenance responsibility of the ME department.

With regard to the feedback to Ship Department of sea-going experience, two main avenues exist. The first of these is known as the S2022 procedure and is a method by which the ship reports a shortcoming in material, design or support to C-in-C Fleet, Portsmouth. They collate the information and highlight recurring defects. The appropriate section in Ship Department is informed and corrective action taken as necessary. The second method by which sea-going experience is injected into Ship Department is by employing serving Naval Officers in the Department, particularly in the design and research areas. This is of great value, particularly with regard to naval operating procedures and routines.

The first uses of electricity in warships were purely for gunnery and firing circuit applications. Arguably the most important use of this electricity was to drive the searchlights which were regarded as an anti-submarine weapon and thus electrical generation became the responsibility of the torpedo department (a subsidiary of the old gunnery department).

The primary reason why the Royal Navy adopted d.c. generation for the subsequent 65 years was primarily in that it afforded relatively easy motor speed control when compared to a.c. generation. A reference which may be of interest and is the earliest account of the use of electricity in warships is a book entitled *Torpedoes and Torpedo Warfare*, written by a Lt Sleeman in 1880.

As Cdr Ranken rightly says, small ships of today have major warships' electrical loads. A modern warship now has a far greater proportion of tasks undertaken by electrical means than ever before. Apart from the obvious increases in weapon and communication systems, there have been recent changes which have also greatly increased the electrical loading, e.g. the transfer of space heating systems to electricity. The high cost of pipework and the difficulty of installing pipework into confined areas makes the electric heating more economic. In the latest generation of ships, electricity for both propulsion and dynamic positioning is coming very much to the fore and this obviously imposes a very heavy demand on the main supply system.

The advent of modern technology has brought about integrated circuits or 'chips' and, while these individually draw only a small current, the complexity of modern weapon communication systems is such that the packing density of such integrated circuits is extremely high. As a result, therefore, the current demanded by the latest generation of equipments is often greater than those they replace.

With regard to damage control, full NBCD procedures are still adopted for all RN vessels. All essential equipments are either dual-fed in the case of 'non-break' supplies or fed via changeover switches in the case of 'limited break' supplies. In certain cases a battery back-up system is also provided. Wherever possible, essential loads are grouped to an EDC and this EDC, apart from having an alternative supply via an ACOS, would also have the facility of being able to be supplied by emergency cables.

It is quite wrong to suggest that it is a result of change in design philospohy that led to the inability to contain fires during the Falklands campaign and that as a result ships were lost. Many fires were contained during the conflict and no ships, past or present, would survive a hit with a modern missile in a critical area such as a magazine or fuel storage tank. It is probably fair to say that a modern warship is better than ever before in containing damage after sustaining action damage.

Gas turbines have been considered for use as prime movers in our modern ships but have shortcomings when compared to the modern fuel-efficient diesel engine. In particular, the fuel consumption of a gas turbine increases rapidly with decreasing load and increasing ambient temperatures. Also, gas turbines require large intake and exhaust ducts, have a high airborne noise level, a limited planned life, and upkeep by exchange and shore maintenance facilities are required.

In the case of the Type 23, the electric drive motor has to provide manoeuvring power as well as propulsion power; thus the motors have to be independently controlled and capable of supplying full power in either direction and rotation. It is also necessary for the electric motors to be able to provide the torques and powers required for reversing propellers when the vessel is being powered at high speed by the gas turbines.

An a.c. motor runs at a speed and direction determined by its supply frequency whilst a d.c. motor's speed and direction are determined by its supply voltage. The range of control required means that the restrictions imposed by a fixed-frequency a.c. motor in an integrated system are not acceptable.

Studies have shown that of the various drive configurations possible, all but the d.c. motor system adopted were unacceptable on the basis of unsatisfactory characteristics (as far as the proposed installation is concerned) and required appreciable development work. The d.c. Ward Leonard drive is undoubtedly the most effective method of motor speed control and provides a degree of control unsurpassed by any other drive system. The flexibility of the Ward Leonard system is such that this arrangement is used, even though in the modern installation the generator has been replaced by a static convertor.

With regard to the starting current limitations of motors in a typical split run system, the power factor is maintained at 0.8 to 0.9 although transient effects of a large motor starting may reduce this figure. Specific guidance on the limitations of the starting currents of a.c. and d.c. motors is to be found in NES 632. Obviously, the limits applied depend on the size of the machine that is required to be started.

In general, for a.c. induction machines the maximum permissible starting current is limited to between 2 and 8 times the rated load current. In the case of d.c. machines, the limitation again depends upon motor size but in general is limited to 2 to 2.5 times the rated load current. Other factors which must be considered when deciding upon limitations to be imposed on starting currents are minimum run-up times and starting torques. In the end, engineering compromise has to be applied.

With regard to static switching, this is now widely employed on RN vessels and is used chiefly for supplying converted supplies, static frequency changers and static invertors. In the main the equipments are less than 10 kVA. Reliability of the latest generation of static frequency changers is high; this has been brought about by sea-going experience and improvements in technology.

Armoured cable is not used on modern warships, with all the modern developments being aimed at the introduction of LFH cables. Weight savings can be vitally important, particularly in the case of cables, as these are often sited high in the ship's superstructure, e.g. those performing control and communication functions. Additional weight here can be very detrimental to ship stability.

In the main, motors and generators are designed to withstand limited flooding; but this would be prohibitively expensive, and impracticable, if this were attempted for all switch and control gear. As a matter of policy, generators and switchgear are sited above the level of flooding and in the centreline of the ship. The severe cost constraints under which ships are now being designed make this the only feasible course of action to minimize the possible effects of action damage.

In response to Mr Rush, a major problem that precludes a more accurate assessment of the total connected load is that the operational role of the ship tends to vary according to the world situation; thus weapon fit in particular can change relatively late in the ship's design. Secondly, as it may take 10 years from concept to launch, systems and equipments are often designed in parallel. The number and size of generators has to be fixed relatively early in the ship's overall design when often many questions still remain unanswered with regard to the electrical loadings of equipments which are still in the design or even concept stage. We are consistently trying to find ways of more accurately assessing the initial total connected load and this, together with computer predictions of diversity and utilization factors, will hopefully overcome the light-loading problems often experienced in the past.

The priorities that tend to dictate a compromise siting as against a preferred siting of generators and switchboards are those that affect the overall safety or fighting efficiency of the ship, for example ship stability criteria, the siting of weapons systems or the running of main-run cables through sensitive communication areas. As in all engineering disciplines, a compromise has to be reached that will give the ship optimum fighting efficiency together with acceptable levels of integrity, availability and quality of supply to satisfy the various modes that the warship can be called upon to perform.

The arrangement of using a changeover switch to supply an essential load is adequate for RN ships and has been found to work well in practice for 'limited break' supplies. The policy adopted is to site the changeover switch as close as possible to the equipment being fed. In such cases the probability is that a direct hit on the changeover switch will in any case have destroyed the equipment it is feeding. Automatic changeover switches can restore the supply in 0.1–3.0 seconds depending upon ACOS settings. Sensitive equipments that require low-break supplies are either dual-fed or have a battery back-up system.

Even though in the past ships have been run in a split configuration, fault levels have been calculated on the basis of two generators running in parallel to allow for the worst situation that might arise if a fault were to occur during a load transfer. In such instances, typical fault levels that would be found in a ship of the frigate/destroyer size are as follows:

At the switchboard: 19 MVA;
At the EDC: 18.5 MVA;
At the fuse panel: 15.5 MVA;
At the direct-fed equipment: 16 MVA.

Although many commercial breakers exist that can handle the fault levels, very few meet the necessary RN environmental specifications, with the weak point of most commercial equipments being their inability to withstand the required shock levels.

In the case of the Type 23 design, the generator sub-transient reactance was set at such a level so that the switchgear was able to handle the fault current. Computer simulation verified that the transient voltage response/load acceptance performance of the main electrical power system remained within Defence Standard 61–5 limits, with it still possible to start even the largest motor load direct on line. This is yet another case where engineering compromise has to be applied, with each individual case judged on its relative merits. At the end of the day, however, a sensible compromise has to be found between manageable fault levels and acceptable transient performance.

Whilst agreeing with the sentiments of using more MCCBs and miniature MCCBs, we are unable to find any that are commercially available that can handle the fault current and are also able to meet the required environmental specification, particularly with regard to shock levels. In the case of distribution circuits of less than 30 A rating, a fuse factor according to Mr Rush's formula is in the order of 1.5–3.0. The fuse ratings, however, are chosen with respect to achieving adequate discrimination with the nearest 'upstream' protective device and the ability of the fuse in question to handle the inrush or starting current in the case of supplying a transformer or motor load respectively.

NATO-preferred voltages are used in all RN ship designs which, in the case of lighting circuits, is 115 V, 60 Hz, 1-phase. Furthermore, developing a new range of approved and environmentally tested lighting equipment to RN standards would be very expensive. In the case of portable tools, the voltage used is 115 V which is derived from a 3-phase 440:117 V transformer. The secondary consists of three electrically isolated single-phase windings of 115 V with the centre tap of each winding bonded to earth. If this method is adopted, only half of the line voltage, therefore, exists between any line and earth.

Finally, one could not justify a change from an unearthed system on the basis of a low incidence of occurrence of earth faults in commercial ships. In RN ships due account must be taken of the high incidence of earth faults that may occur during or after action damage in a hostile environment. In such circumstances it is possible to tolerate a single earth fault for as long as is necessary, which could mean the difference in the availability of a weapon system.

I thank Mr Kitchen for his comments on the paper. As he rightly says, discriminating fault-limiting breakers would eliminate the majority of the fuses in a warship's electrical distribution system. Despite repeated efforts, however, we are unable to find any that are commercially available that meet the required RN environmental specification, particularly with regard to the shock levels. Such devices cannot be used, therefore, until developed in a shockproof form.

Supplement

The author has agreed to include here a summary of the more important areas of his paper together with additional information not contained in the original paper, with special reference to cables and the electrical design of the new Type 23 frigate.

The subject of my paper is very wide and involves much detailed electrical design built up over many years of experience, including essential feedback of information from the Fleet. The paper covers in some detail the manner in which the electrical design process is carried out but I shall now summarize the more important and, hopefully, more interesting areas in the paper, concentrating on some additional aspects.

I shall also say more about the work that DG Ships have been doing in the field of LFH cables as these components are an important part of the electrical system design. This is particularly relevant because of the emotional furore that broke in the media during and after the Falklands campaign over the cables used in RN warships and the way they are supposed to burn.

As an example of how overall electrical system design evolves, I shall go through the main electrical design process of the Type 23 frigate which, because of its integrated main supply system and electrical propulsion, is a departure from past RN practices. This will give an insight into the way the electrical systems for a major warship are finally brought to reality. Finally, I shall briefly mention the future development of electrical design in the RN.

A modern warship is designed to achieve the vessel's operational role in both peace and war. As in most complex systems, ship design is of necessity a technical compromise—in this case between the hull, machinery, electrical and weapon disciplines—within the limits of cost, manning and support activities, as well as on occasions by the interaction of the disciplines themselves. One of the most important systems is the main electrical supply and distribution system, which provides the source of power for all systems such as weapons communications, navigation and steering and ship's systems. It cannot be designed in isolation but must be developed within constraints, thus ensuring provision of electric power to a multitude of services with acceptable integrity, availability and quality to satisfy the various modes that a warship can be called on to perform.

All these conflicts and compromises, and other technical considerations, have to be taken into account in the electrical power system design, the basic aim of which is to produce the electrical power of the necessary quality and reliability on demand to every service in the ship that requires it, thereby enabling the objectives and operational commitment of the ship to be met. I will now describe some, but not all, of the major design processes that have to be followed.

Estimating load

A warship cannot be an instant design; it is the result of many feasibility studies carried out in conjunction with the Naval Staff, aimed at countering projected threats. This process takes several years, with weapon and ship systems finally emerging some years from the inception of the original requirements. Of prime importance in the design of the electrical distribution system is the estimation of the ship's electrical load, for it is on the basis of this early estimate that decisions will be made on the size, number and configuration of the primary components of electrical power for the life of the ship, such as generators and switchboards. Therefore it is extremely important to obtain an accurate assessment of the loads as soon as possible.

As a first stage in the design, a broad-brush electrical load chart is drawn up, a feature common to commercial practices. Figure 1 gives an impression of the design load growth of a typical frigate. It can be seen that from the issue of the Naval Staff Requirement to acceptance there is an increase, typically of 25%, and a further 20% growth over the rest of the ship's life. This allows for all improvements that tend to be added during the ship's life, particularly in the design area. The present trend, however, is to depart from this and to restrict the permitted growth, as this greatly increases the cost of a vessel as well as causing low-loading problems early in the ship's life with resultant loss in availability.

In determining the total connected load, data are drawn from similarly sized ships with similar operational roles, the total connected load for each operational state, such as harbour, cruising and action, for the new design being extrapolated from these data. This load-gathering was not mentioned in the paper; it is a break from tradition and will, hopefully, improve the utilization and diversity factors which were previously applied to the ship's design.

Ship load recording

Electrical loads for future designs are based on the information gathered automatically on surface ships. In the first ships, data were collected by paper chart recorders and then by punched paper tape;

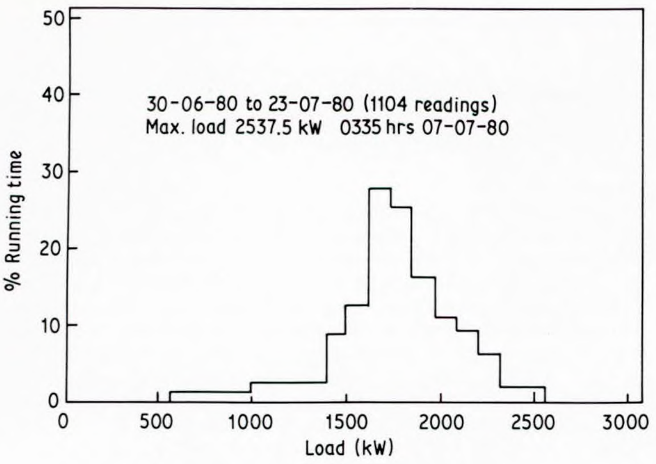

FIG. 13 Total load recording at sea

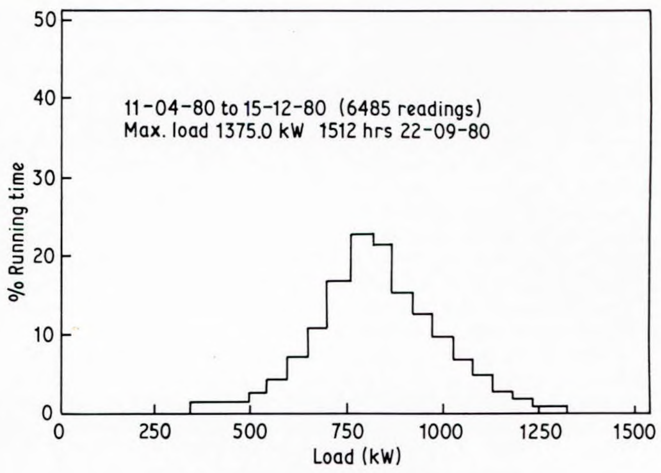

FIG. 14 Generator K2 load recording

whilst today, recordings are made using Microdata data-loggers, with the results analysed on a Tektronix 4051 desk-top computer at NGTE West Drayton. The results are presented in a convenient and readable form. The process ensures a build-up of historical data which is invaluable in assessing new ship design, particularly with regard to generator sizing and in achieving a balanced distribution system. The ship's total load is in kW and measurements are recorded from each main generator and shore supply using ship's installed transducers. Any parameter may be recorded, e.g. shaft speed, provided it can be converted into an analogue form (typically 0–2 V).

The data-logger has 12 channels of which nine are used for data recording, the others being used for timing and datum reference. Recordings are made at intervals of 10 min; this enables one month's recordings to be made on a single C90 cassette. The data-logger digitizes the inputs and, at the end of each time interval, the tape is progressed recording the input information. The recordings are then sent to NGTE West Drayton for analysis.

The results are presented in the form of histograms and are produced for monthly periods from the readings that are taken at 10 min intervals. Figures 13 and 14 show typical histograms, together with some of the useful information that can be displayed. This can take the form of a histogram for each individual load, such as galley load, as well as total loads for operational states such as loading at sea, and total load of each generator. Additionally, histograms can be obtained from the monthly histograms and facilities are provided for producing daily load curves (Fig. 15) as required. In the computer, each load at a particular time is compared against a reference enabling the load data to be segregated into discrete load bands.

With this information, and allowing for design and ship growth, a final maximum total is derived which is usually the end-of-life load and is used as the basis for determining installed generator capacity and the number and size of generators.

Number and size of generators

Before taking the irreversible step on the number and size of generators, it is important to know that the estimated maximum total load is correct. Clearly in the early stages of design this can be difficult but as the load chart evolves it becomes more evident, although the decisions would need normally to be taken before the load chart is finalized and must allow for future design and through-life growth margins. In the past traditional methods have proved too generous and resulted in larger and more expensive generators with a tendency subsequently for the diesel engines to be lightly loaded, with additional maintenance and down-time problems. Figure 2 shows the experience from sea and shows how low percentage loadings will adversely affect the time between overhauls.

At the selection stage of the design there are many other factors to consider, with, usually, a compromise between conflicting requirements. The advantages and disadvantages of large numbers of small sets compared with a small number of large sets may be outlined as follows:

Large number of small sets:

(a) Optimum loading and economic running.
(b) Greater flexibility in ship's layout.
(c) Uneconomic use of machinery space.
(d) Restrictions in starting induction motors.
(e) Greater complexity of control and switch gear.
(f) Greater maintenance load.

Small number of large sets:

(a) Some difficulty to optimize loading.
(b) Less flexibility.
(c) More economic use of machinery space.
(d) Induction motor starting problems minimized.
(e) Simplified switch and control gear.
(f) Reduced maintenance load.

Small sets give more economic and better utilization of load and lend themselves to more flexibility of layout in the ship than larger sets, whilst they are less economical in the use of machinery space and can experience problems in starting up large induction motors, as well as requiring more complex and larger switch and control gear equipment; they also present a larger maintenance load to dockyards and ships' staff.

An important factor to take into consideration in the selection of generator sets is the behaviour of ship's electrical load. This behaviour can be broken down into a pattern of daily and long-term variation. The daily pattern has been well established and confirmed by records over a period of time under harbour, cruising and action conditions.

It is extremely difficult to lay down hard and fast rules on the number and size of generating sets and each particular design will have to be judged on its merits. However, there will usually be several combinations of number and size of generating sets which will meet the maximum total load and I have already indicated a number of factors that need to be considered in making the decision. However, although the number of generators has to be another compromise, in practice the smallest number of sets are installed.

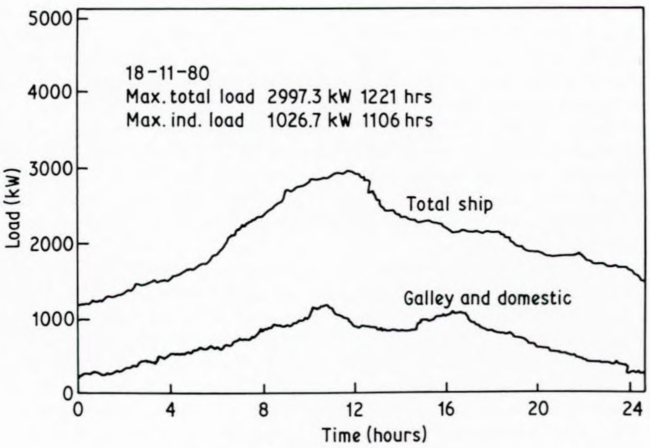

FIG. 15 Daily load variation

The methods of operating generators in the ship's main supply system, either in a split or parallel operation, were adequately covered in the paper. I prefer to say a few words about the main supply system arrangement in its relation to the vulnerability of the ship.

Due consideration must be given to the geographical siting of the generator sets, and associated switchboards and controls, in relation to the vulnerability of the ship. This is often constrained by ship's stability criteria. Usually it is best achieved by having sufficient dispersal of generating plants and switchboards, giving a degree of system integrity and ensuring that, in the event of limited flooding in the ship, enough generating capability remains operational to supply the salvage load. Typically, in the case of a frigate there will be four generators fitted and two switchboards, with separation between associated switchboard and generators kept to a minimum.

Siting of the switchboards is as important as the siting of the generator sets since without them there is no means of distributing the power generated to the users. Normally there are at least two watertight bulkheads between switchboards, and the switchboards and generators should be above the level of flooding and preferably be located on the centre line with the same longitudinal separation as their associated generators. If this is not possible, they should be sited on opposite sides of the centre line but preferably not in a ship's side compartment. Normally the secondary control positions of the main electrical supply system are sited in the switchboard rooms and these must be far enough away from the primary control position in the ship control centre (SCC) to ensure that primary and secondary control cannot be lost by a single survivable hit (see Fig. 5). It is normal practice in HM Ships to sectionalize and to interconnect switchboards such that, in the event of failure or action damage to any part of the switchboard, the faulty part can be isolated and the remainder can continue in use. Greater flexibility in loading of generators can of course be obtained by introducing extra sections to the switchboard. With this arrangement, if one generator is not available the load can eventually be distributed between the remaining generators by suitable grouping of the sections (see Fig. 6).

Method of power distribution

In a typical modern destroyer or frigate there are likely to be four diesel generator sets (each sized, typically, 1 MW) supplying two switchboards each of three sections connected by bus-couplers. The two switchboards are connected by two interconnector cables with two interconnector breakers at each switchboard. The diesel generators are connected to the switchboard via supply breakers; and two shore supplies can be connected to the centre sections of the switchboard via shore supply breakers. Power is distributed throughout the ship in bulk via electrical distribution centres (EDCs), which are sited as near as possible to the electrical centre of the services requiring supplies and are fed from the three sections of each switchboard by air circuit breakers (see Fig. 7). From the EDCs power is distributed around the ship to individual large loads, e.g. to individual motors, and to smaller loads via fuse panels via MCCBs of 250 A and 100 A framesize, arranged in standard panels. The MCCBs offer protection against overload and are readily reset. Considerable care is taken in the supply and distribution system such that the current-interrupting devices are rated with regard to the system fault levels and that discrimination is achieved between major and minor devices.

A principal feature of the distribution system for RN vessels is that it operates with an unearthed neutral point, i.e. no direct connection between the neutral and earth. This is chiefly to ensure continuity of supply in the event of an earth fault. In this type of system the earth fault current is so small that a single fault can be tolerated, which is extremely useful under action damage conditions.

In RN ships, as in all Navies, certain important services are fed by alternative supplies from different generators and through different switchboards and cables via changeover switches (COS). This is to ensure continuity of service if a generator, switchboard or feeder cable should be lost by action damage, and thus the COS is placed as near the service as possible.

Changeover switches are of two types—automatic and manual. Auto-changeover switches (ACOS) are used only with vital services, e.g. lubricating oil and pumps. They operate to reconnect the service to the alternative source when either voltage and/or frequency-sensing control circuits indicate that the normal supply is outside tolerance. Manual changeover switches are operated by hand for circuits where some delay is acceptable. Certain weapon systems that require a guaranteed continuity of supply, e.g. supplies to computers, will be provided by a battery-supported conversion equipment.

The development of the distribution system will commence only after the size and number of the generators have been fixed and the supply system configuration has been established. The distribution system must perform under specified limits both under steady-state, transient load switching and fault conditions. The whole design process is an iterative one and each item requiring a supply must be fully identified.

Protection

The main electrical supply and distribution system and user equipment must be protected against damage which may occur through abnormal conditions. The best way to achieve good protection is to have a selective method of disconnection which gives isolation as near to the fault as possible, as well as giving minimum disturbances to healthy parts of the system. Protection equipment is to be capable of responding to one or more of the following parameters: current, frequency (speed), voltage, temperature and power; and to be time-dependent and easily adjustable so that operating settings can be made to achieve the required discrimination on an overall system basis.

As an example, consider the overcurrent protection fitted in a typical ship. To ensure that the nearest 'upstream' protection device will clear the fault, discrimination must exist throughout the main supply system. It can be seen from Fig. 8 that, in the event of a fault occurring in the supply breaker, which incorporates short-time, high-current protection (0.4 s), and long-time low-overcurrent protection (8–20 s), adequate safeguards will be given. The high-current protection setting will be chosen so as not to exceed the short-circuit capability of the generator, thus giving a measure of short-circuit protection. The low-overcurrent protection will ensure that sustained overload (kVA), which may result from flooding faults for example, will not cause damage to the generators. The interconnector/bus-coupler and feeder breakers are also provided with characteristics similar to the supply breaker, but with lower current and shorter time settings. In this way adequate discrimination is achieved.

It can also be seen that high MCCB settings do not totally discriminate the feeder breaker for all currents—overlap occurring in the small range 800–1200 A. Generally, however, short-circuits will produce currents well in excess of these values and overload will produce currents of lower values and, in practice, discrimination will be achieved. Further, it can be seen that the MCCBs have electromagnetic and thermal trip devices: the former give the required characteristics for short-circuit protection, whilst the latter gives the required overcurrent protection characteristic.

The overlap of the feeder breaker and the MCCB characteristics often occurs because of the conflicting requirements that:

(a) The feeder breaker and all upstream breaker characteristics must be below the generator thermal characteristics in order to protect the generator windings; and
(b) The MCCB characteristic must allow a motor to take the motor starting current for the run-up time without tripping the MCCB.

MCCBs used in present ships have back-up fuses to protect the MCCB itself against fault currents in excess of its breaking capacity. These fuses operate for these faults and cut off the current, thus eliminating the current to be cleared by the MCCBs. Therefore normal faults will be cleared by the MCCB with the fuse remaining intact.

Final distribution to circuits of less than 30 A rating will be made via HRC fuses.

Power system control

Control of the main supply systems is from the primary control position located in the ship control centre (SCC) in which will also be the main machinery plant control system. The electrical power supply system is supervised and controlled from this position, including the remote start of the diesel generator sets, control of the voltage and frequency, and the synchronization of generators for parallel running, together with the control of all main switchgear with full indication of breaker states on a mimic diagram of the main supply system.

Secondary control of the main supply system is available at switchboards; however, under normal operating conditions these spaces are not manned. Control of the air circuit breakers is exercised at the secondary control position of that switchboard only, indication being provided also of the breaker states at the second switchboard.

Cables

As cables were the subject of a rather emotional debate during and after the Falklands campaign, it seems appropriate to speak a little about the cables fitted in ships and about the work that has been going on to ensure that future ships and submarines are fitted with cables having improved fire characteristics. As ships have become more and

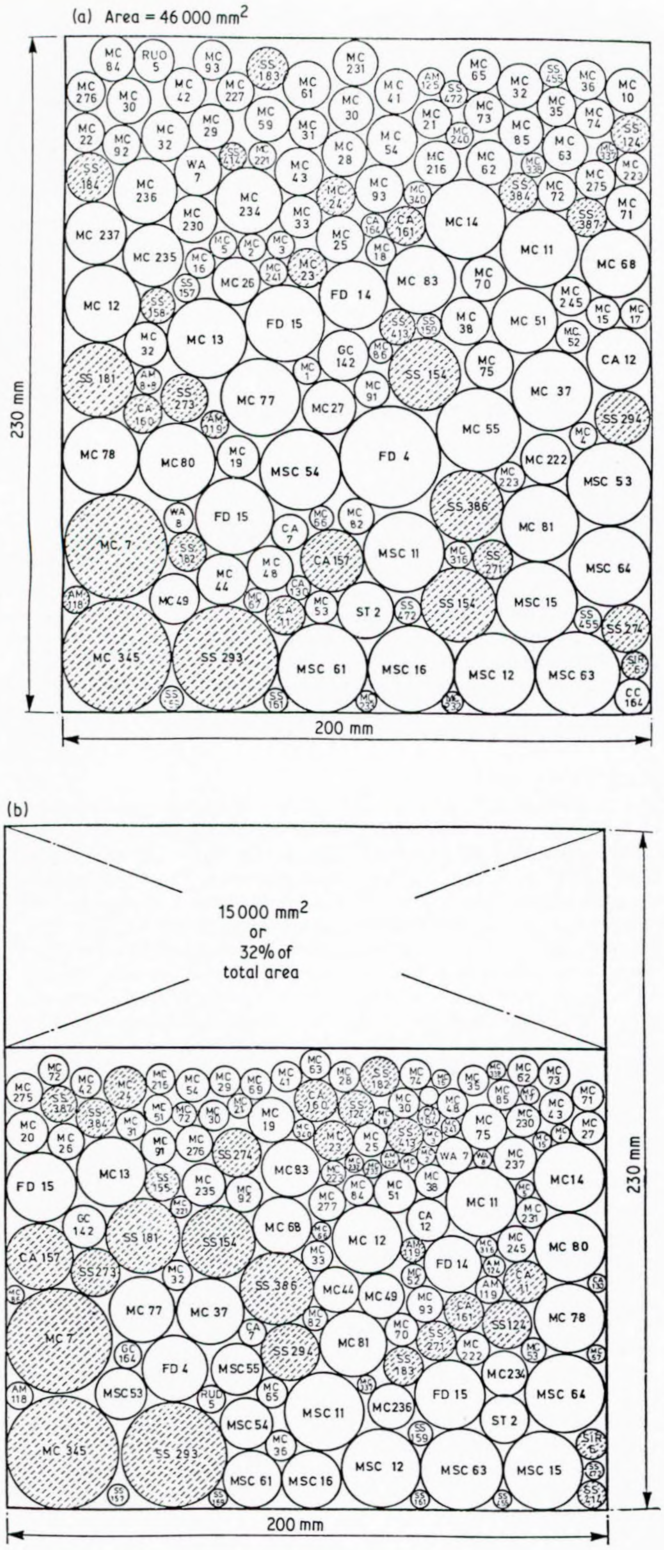

FIG. 16 Space saving: (a) original cables and (b) new-technology cables

more complex, so the number of cables and connections has increased drastically. It is important to appreciate that the cable itself is only a part, albeit the most important part, of a cable system which incorporates terminations, connections, plugs and sockets and cable hangers.

At present our ships are fitted with many types of insulating and sheathing materials available for cables to meet the various environments and requirements that occur in a warship. The types, with their characteristics and uses, are listed in Table III.

The majority of cables, although fire-resisting, produce smoke and in some instances toxic and acid gases. After much involvement with the cable manufacturers the RN has now introduced a policy for a rationalized range of LFH cables which will be introduced in all new designs of RN warships. These cables will be flame-retardant, will generate low amounts of smoke and will have a low toxicity and acid gas content.

Of the four characteristics, the need to reduce flammability, smoke and toxicity might appear to be rather obvious, as clearly if a material has improved flammability it will produce less smoke and fumes. Having low toxicity and low smoke emission are very important, as these characteristics will not only give personnel in compartments time to escape from the scene of the fire, but they will also enable suitably equipped firefighters to see the seat of the fire and fight it.

The most invidious fire characteristic is undoubtedly the generation of acid gases, notably hydrochloric acid gas, because unless the fire products are acid-free, or they are contained within the near vicinity of the fire, they will percolate throughout the ship and at a later date cause electrical breakdown of terminals, components, printed circuit boards and connectors. This will always be expensive and may be operationally disastrous.

Whilst drawing up the future policy for LFH cables, it was noticed in the survey that 90% of all cables were limited to a core size of less than 2.5 mm², i.e. rated at currents up to 20 A, and it was on cables of this size that we in DG Ships concentrated our attention. The logic we have applied has been to develop new-technology equipment wires using materials that react favourably in fires and which give very low smoke, toxicity and acid gas emission. These equipment wires have then been taken to form the cores for multicore cables and sheathed with a suitable LFH sheathing material to NES 518 (which is our performance specification). The resultant cables have the added bonus of occupying far less space (Fig. 16) and are considerably lighter—this means that a saving of approximately 25 tons can be made on a typical frigate installation. This can be invaluable to the naval architect for both weight and space reasons; it might even permit the inclusion of an additional weapon system.

For the general-purpose cables with cross-sectional area greater than 2.5 mm², i.e. 20 A and above, it is intended to use EPR rubber insulated cables, procured to existing cable specifications, but having an LFH sheath (to NES 518) instead of CSP. For circuits requiring a degree of circuit integrity in a fire, we will continue to use silicon-insulated-cables procured to the usual specification but with an LFH sheath, to NES 518, in lieu of CSP.

That is the present situation and we intend to continue making progress and improvements to the design of cables with respect to a fire. We have come a long way since the first cables were used in RN warships just under 100 years ago. Then the cables were rubber-insulated, cotton-taped or braided and coated with preservative varnish; they were run in teak casings and embedded in putty. Despite this, the ingress of salt water caused short circuits and frequently set fire to the wood casings!

Type 23 frigate electrical design

I shall now refer to the electrical design of the latest RN ship, the Type 23 frigate, as an example to show how electrical design evolves in an RN vessel.

The generally accepted reasons for adopting electrical propulsion are:

(a) When manoeuvring;

(b) Where the main generating plant can be utilized to provide power for auxiliaries in addition to propulsion.

For the Type 23 there is an additional overall reason, namely the ability of providing a system with very low noise characteristics, with the ease of reversing without the complication of controllable-pitch propellers or reversing gearboxes. Other reasons are flexibility of layout and control and optimization of number of prime movers to suit load demand.

Since the electrical drive has to provide manoeuvring power as well as propulsion power, it is necessary for the two electric motors to be independently controlled and capable of supplying full power in either direction of rotation. The electric motors could be either a.c. or d.c. machines provided the requirements for independent control are satisfied.

Selection of the system configuration, rating of equipment, mode of operation and control have all been influenced significantly by the requirements of the electrical motors as they are by far the largest loads, as well as having operational features. Many detailed studies were undertaken during concept and feasibility covering total system requirements, including electrical propulsion and electrical main supply system; a.c. and d.c. propulsion schemes were considered with integrated and split configurations.

The selected system (Fig. 17) is based on the integrated type, i.e. main supply electrical propulsion systems that are fed from the same four diesel generator sets, which form a central power supply for the ship as a whole. This has enabled a 600 V, 60 Hz, 3-phase system, with continuous parallel running, two switchboards and a single main interconnector.

The ship's electrical supplies are at 440 V, 60 Hz, 3-phase which will be derived from two motor generator sets. The two switchboards will be composite boards accommodating the 600 V primary breakers and the 440 V distribution breakers and equipment. Variable d.c. electrical propulsion motors were finally chosen with thyristor-control inverter drive.

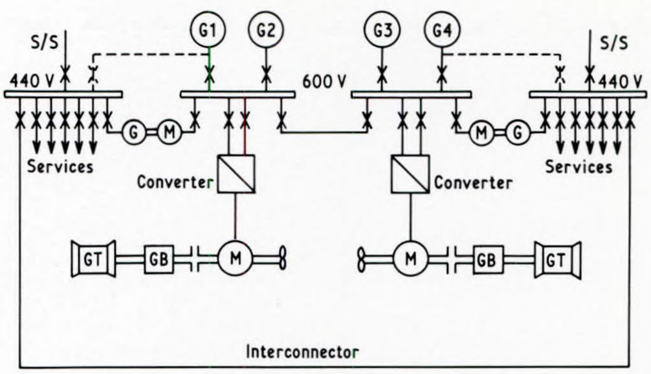

FIG. 17 Type 23 main supply system

Advantages of integrated system configuration

The integrated system configuration has the following advantages:

(a) Minimizes the number of diesel prime movers required.
(b) Gives best utilization of generating capacity.
(c) Allows economic continuous low-speed ship operations.
(d) A certain amount of power is always available for crash stopping when on gas turbine drive.

The main disadvantage of the integrated system is the need for large motor generator sets to provide the quality of power supplies to normal RN standard.

System operating voltage

600 V is a non-standard RN voltage but its use offers attractive savings in equipment cost and volume. In particular, the converter utilizes thyristors which are quite capable of operating at higher voltage, thereby reducing the number of cells required to handle the current. This and other current-related components would basically require a 36% higher rating and volume (and weight) if operated at only 440 V. Operation at 600 V with two motor generator sets allows four diesel generator sets to be operated in parallel within the full rating capacity of the switchgear.

Quality of power supply: harmonic distortion and EMC

Thyristor control of the d.c. propulsion motor produces a large amount of voltage waveform and harmonic distortion. The amount of distortion is related to the number of generator sets operating and propulsion motor load, and grossly exceeds the permitted limits quoted in the RN's normal standards specification for power supplies. Additionally, the rapid switching of the thyristor circuits in the propulsion motor power controls can be expected to produce high levels of radio frequency interference. It is intended to suppress this at source to meet the DG Ships' specification for interference limits.

Initially it was considered that the problems of electromagnetic compatibility (EMC) and, to some extent, waveform distortion could be tackled by filtering and screening at the source of the interference. However, it was acknowledged that the solution of the EMC problem is not easily amenable to calculation so a solution with minimal risk to the ship design was the only one that could sensibly be pursued. The chosen solution is to supply all ship's loads with power at 440 V, 60 Hz, 3-phase derived from motor generator sets, the motor generator sets giving isolation from EMI and providing supplies to meet the RN requirements for quality of power. The motor generator sets are sized such that the ship's maximum activity load is supplied from two sets but only the ship's maximum essential load from one. The size of the motor generator sets also ensures that the ship's service motors can be started direct on line.

Switchboards and distribution systems

There are two composite switchboards on the Type 23 frigate operated at the primary system voltage of 600 V and the main electrical supply voltage operated at 440 V fed from motor generator sets. A considerable amount of system engineering thought was given to this power system in arriving at the chosen voltage and the air circuit breaker selection. The same air circuit breaker has been chosen for both the 600 V and 440 V operation, thereby ensuring component commonality with considerable logistic/training/documentation advantages which overall make for a cheaper switchboard and lower through-life costing.

Electrical power supplies at 440 V, 60 Hz, 3-phase will be derived from the two motor generator sets; supplies will be distributed from the main switchboards at 440 V to EDCs via MCCBs. As has been said previously, the motor generator sets are sized such that the ship's essential load can be supplied from one set in an event of failure in the other. It is intended that, wherever possible, each EDC will supply a functionally identifiable group of loads. Ideally, this will allow the effect of loss of the supply to an EDC to be assessed quickly. However, this requirement must be judged against the need to site the EDC as close as possible to the centre of the area of load and thus keep distribution cables downstream of the EDC to a minimum length.

Propulsion motor

The propulsion system in the Type 23 is a twin-shaft propulsion for COLAG operation, with each shaft set comprising a single SM1A gas turbine, reduction gearbox and clutch, and with an in-line d.c. propulsion motor directly driving a fixed-pitch propeller. This represents the main propulsion of the ship as electrical propulsion, with a gas turbine sprint capability. Conventional d.c. motors were chosen for the electrical propulsion on the basis of being the best-developed from the noise aspect, offering the most flexible control of torque/speed characteristic, smoothest low-speed running, best low-speed torque, and utilizing smaller and less complicated converters. The a.c. motors offered no clear advantage and involve a considerable risk, particularly in the converter/motor development area.

The disadvantage with d.c. motors—of additional maintenance for the commutator and brush gear—is far outweighed by the many advantages.

System operation

The diesel generator sets will be operated with up to four continuously in parallel via the primary interconnector, to provide propulsion power and electrical power supplies. The number of sets to be operated will depend on the ship's electrical load and the required speed. The loaded generator sets will run independently of each other to supply the respective distribution switchboard sections, each set capable of maintaining the ship's essential load in the event of failure of one set.

Automatic load-shedding circuits will be used to reduce propulsion power and non-essential ship's services in the event of a diesel generator failure or trip when the ship is on electric drive. Automatic load-shedding will also be available for other operational scenarios.

The electrical main supply system will be designed for continuous parallel operation with adequate protection equipment to detect and isolate a failing diesel generator set.

System control

The electrical main supply and propulsion system will be operated from the ship control centre and routine tasks, such as diesel generator start-up, synchronizing and parallelling of the generator sets, will be automated. Because the system is designed for continuous parallel operation, the task of system management becomes relatively simple and will remain under the control of the watchkeeper in the ship control centre. There will be a considerable degree of automation in the Type 23 but the full extent has not yet been finalized. However, there will be considerable diagnostic information displayed via a secondary surveillance system.

Reversionary control of the system will be possible at the secondary control position.

The way ahead for electrical systems

The main supply system and distribution system described in this paper has evolved over the years since the initial introduction of a.c. in RN vessels. Up to the present day it has been acceptable but with some shortcomings, namely:

(i) Operator and maintainer information has been limited and fault diagnosis difficult.
(ii) Operation of the system requires a high degree of training and skill.
(iii) Generator and switchboard load balance is difficult to achieve.
(iv) Limited duplicated supplies to users.

As a result of intra- and extramural studies it is confidently predicted that these shortfalls can best be overcome by adopting parallel running of diesel generators and imposing automation to important operations and functions to aid both the operator and maintainer. The functions to be covered are:

(a) Those functions where speed and accuracy of response are essential.
(b) Monitoring of surveillance parameters in order to detect deviations from the normal and be able to provide preferential load-shedding facilities.
(c) Diagnostic back-up information in order to aid fault-finding.

The automation should result in increased integrity of the supply by reducing the incidence of operator error and provision of sufficient information at the right place to give anticipation of plant failure and replacing it without interruption to the supply. This approach is to be undertaken in the new Type 23 design frigate.

Published for THE INSTITUTE OF MARINE ENGINEERS by Marine Management (Holdings) Ltd
(England Reg. No. 1100685) both at 76 Mark Lane London EC3R 7JN.
Photoset by Paston Press, Norwich
Printed in England