ELECTRICAL SYSTEM DESIGN FOR WARSHIPS

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Introduction

A modern warship is a complex package of propulsion, weapons, communications, 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 also for ship's systems such as chilled water and propulsion machinery auxiliaries. This paper will therefore concentrate 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 applicaiton of electricity afloat in H.M. warships was in the early 1870s, with the introduction of an electric gun-firing circuit. This was energized by a pile battery which comprised 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 H.M.S. *Inflexible.* Built in 1881, she 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 in the Royal Navy 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 U.S. 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 H.M. 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.

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

(*a*) *Wartime action mode:* In this mode, it is necessary to have the maximum redundancy immediately available, so that the effects of damage and/or failure can be rapidly reduced. Response must be at the highest level.

(*b*) *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 sucessfully 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 after the inception of the original requirement.

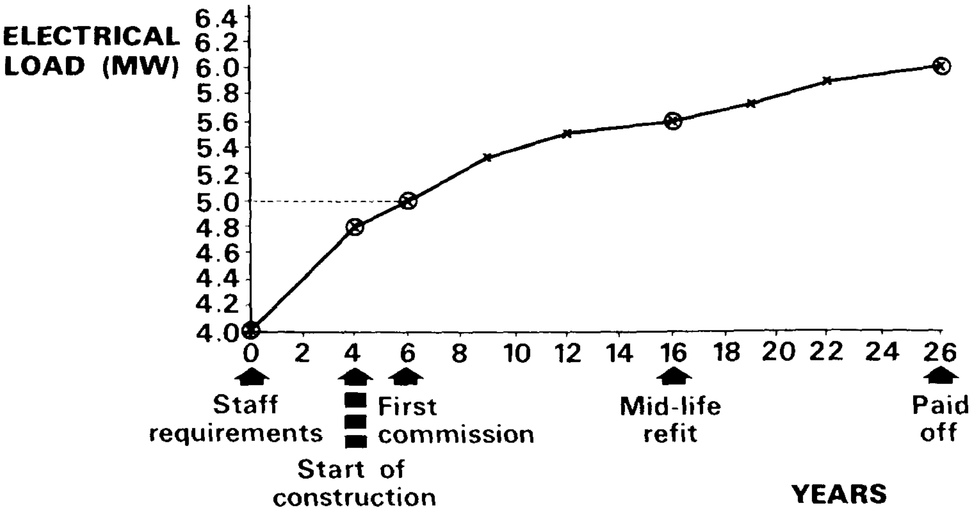

FIG. 1—GROWTH OF ELECTRICAL CONNECTED LOAD THROUGHOUT DESIGN AND LIFE

FIG. 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.

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 and 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 ships of similar size 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 from the others 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. This condition causes excessive carbonization and the time between overhauls is rapidly decreased. FIG.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.

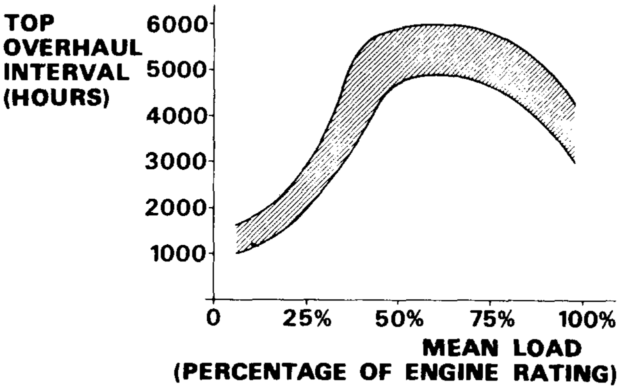

FIG. 2—RELATIONSHIP BETWEEN DIESEL GENERATOR LOAD AND TOP OVERHAUL INTERVAL

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. 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. Fuel-efficient diesels are currently chosen.

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. The decision would normally need to be taken, however, 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!

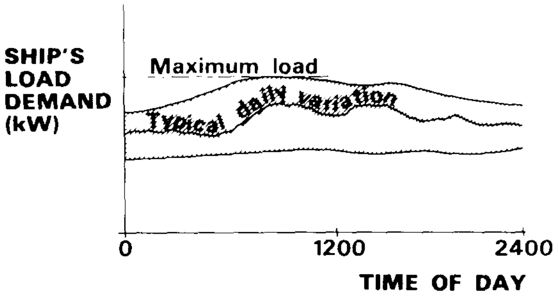

FIG. 3—DAILY VARIATION OF ELECTRICAL LOAD

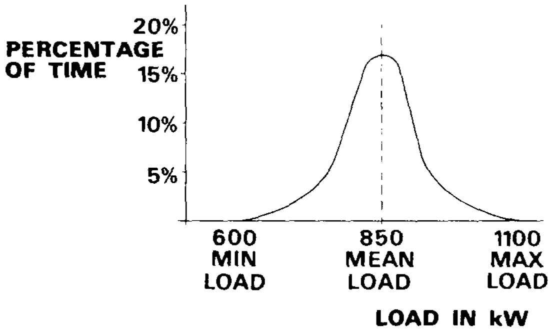

FIG. 4—LOAD DISTRIBUTION OF 1 MW GENERATOR SET IN A TYPICAL FRIGATE OR DESTROYER

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. FIG. 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 in 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 is necessary for each particular design to be judged on its merits; however, there will usually be several alternative 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:

(*a*) Economical loading.

(*b*) Flexibility of operation to cater for failure/maintenance.
(*c*) Requirement to keep loss of capacity to a minimum.
(*d*) Requirement to install a reserve capacity.
(*e*) High vulnerability of ship.
(*f*) Economical use of machinery space.
(*g*) Necessity to keep switchboard arrangements simple.
(*h*) Necessity to keep system management simple.
(*i*) Minimum loading.
(*j*) Unbalance of loading.
(*k*) Transfer of load via hand-operated or automatic-changeover switches.
(*l*) Maintenance and breakdown margins.
(*m*) Running hours and refit intervals.
(*n*) Availability and reliability.

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

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 normally 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 in the ship caused by equipment failure is, therefore, very low.

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 the 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.

TABLE I—*Comparison of split and 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 fewer 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.)

Main Supply System Arrangement

Due consideration must be given to the geographical siting of the generator sets and associated switchboards 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 in 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 survivable hit. This can readily be seen from FIG. 5.

It is normal practice in H.M. Ships to sectionalize and interconnect switchboards so 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).

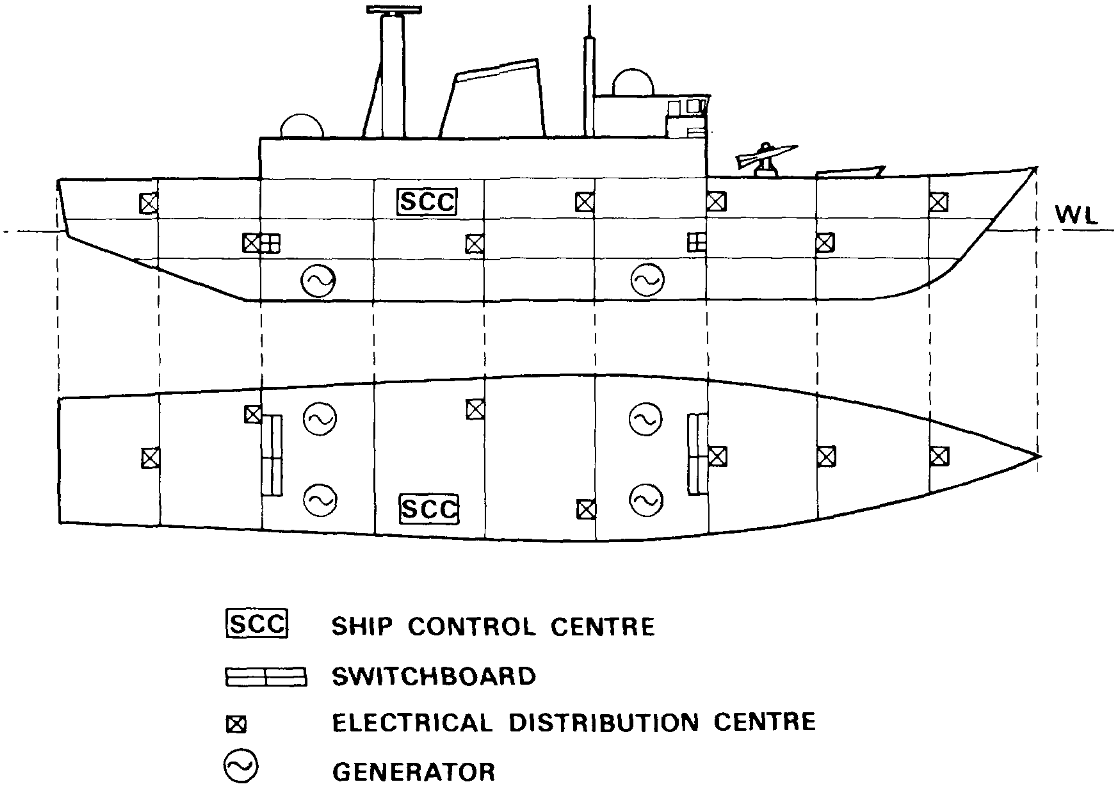

FIG. 5—TYPICAL POWER SYSTEM IN A MODERN DESTROYER

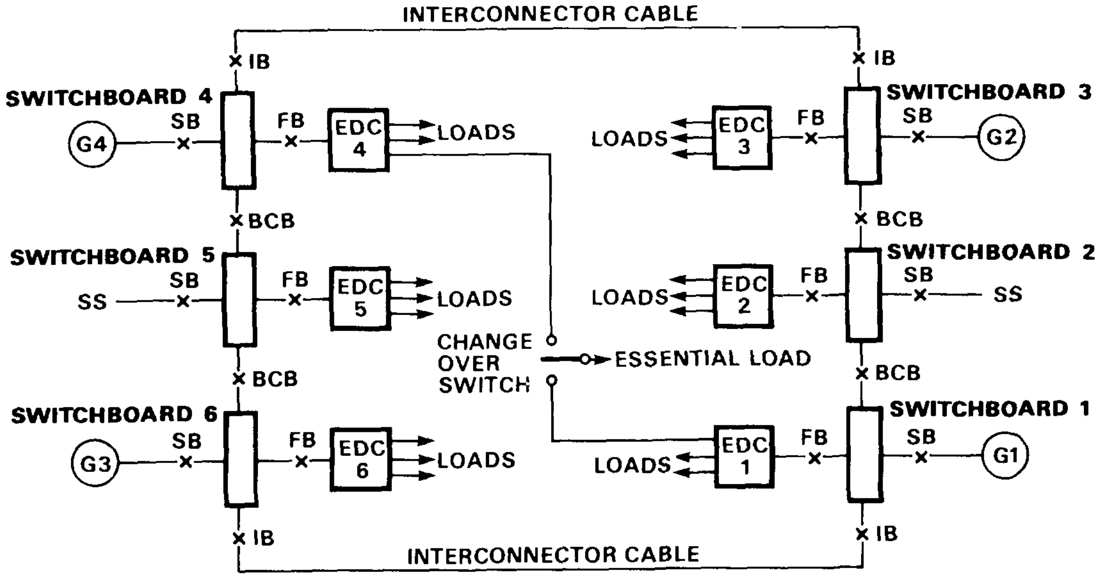

FIG. 6—SWITCHBOARD ARRANGEMENT

BCB: bus coupler breaker
EDC: electrical distribution centre
FB: feeder breaker
G: generator
IB: interconnector breaker
SB: supply breaker
SS: shore supply

Method of Power Distribution

In a typical modern destroyer or frigate, there are likely to be four diesel generator sets (each sized, typically, at 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 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 direclty from an MCCB.

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

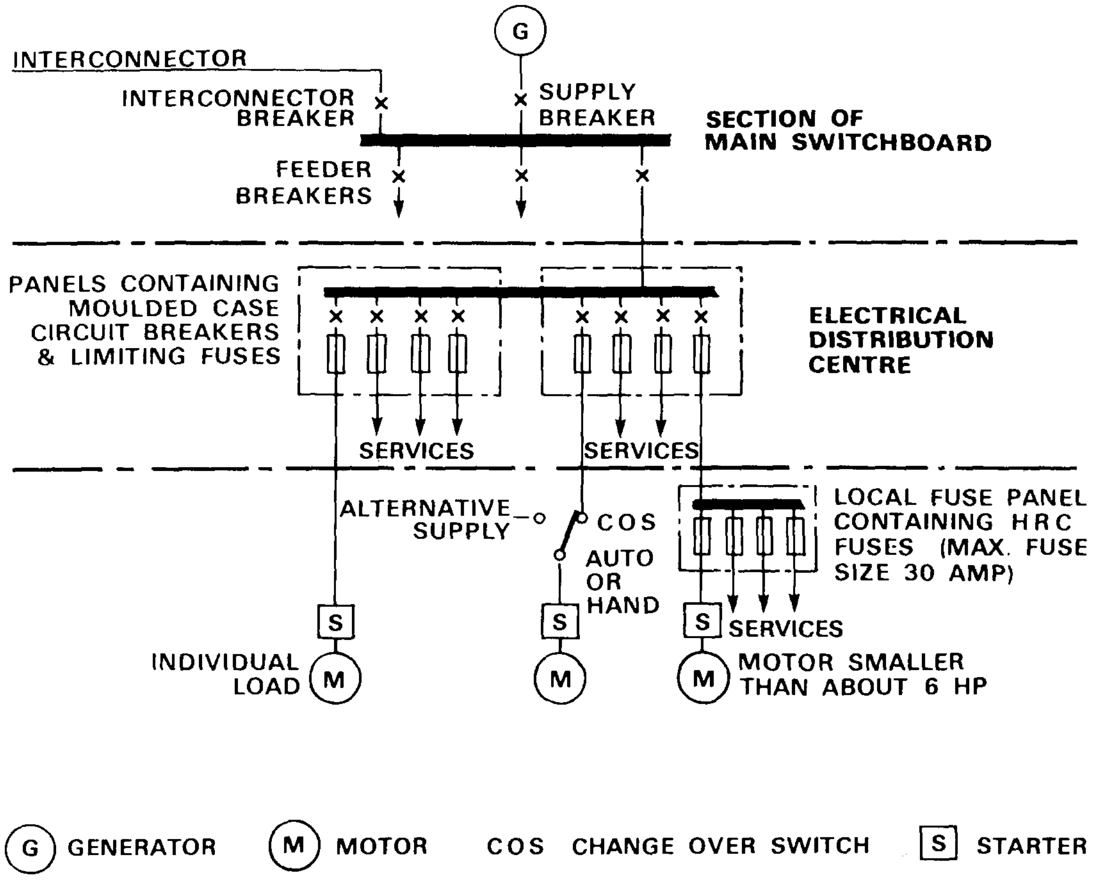

FIG. 7—TYPICAL DISTRIBUTION SYSTEM

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 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, are provided with a battery-supported conversion equipment.

The development of the distribution system commences 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 the 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 functioning 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 ouside 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 this 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 disturbance 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.

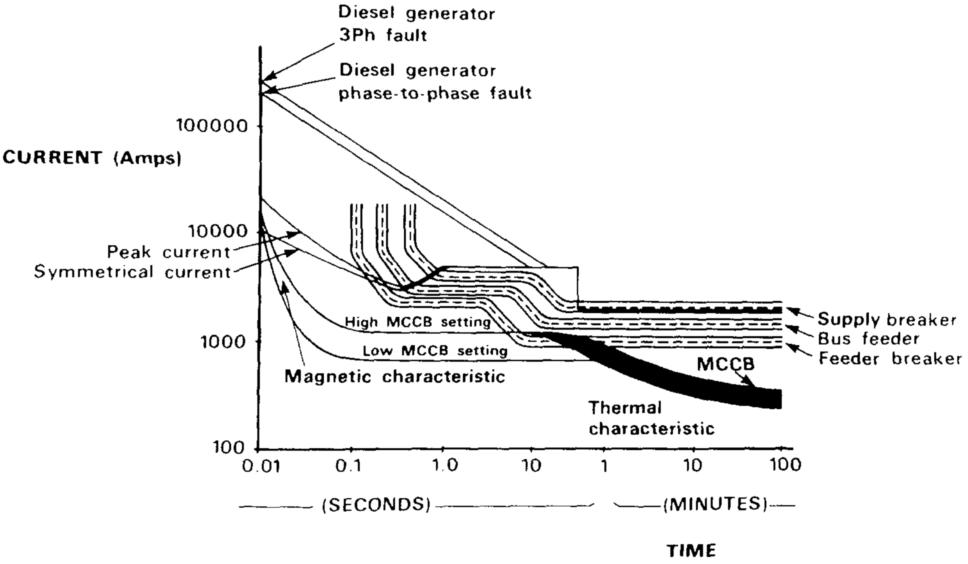

FIG. 8—DISCRIMINATION DIAGRAM

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-over-current protection, adequate safeguards will be given. The high-current protection setting is 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 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 of 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.

Power System Control

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

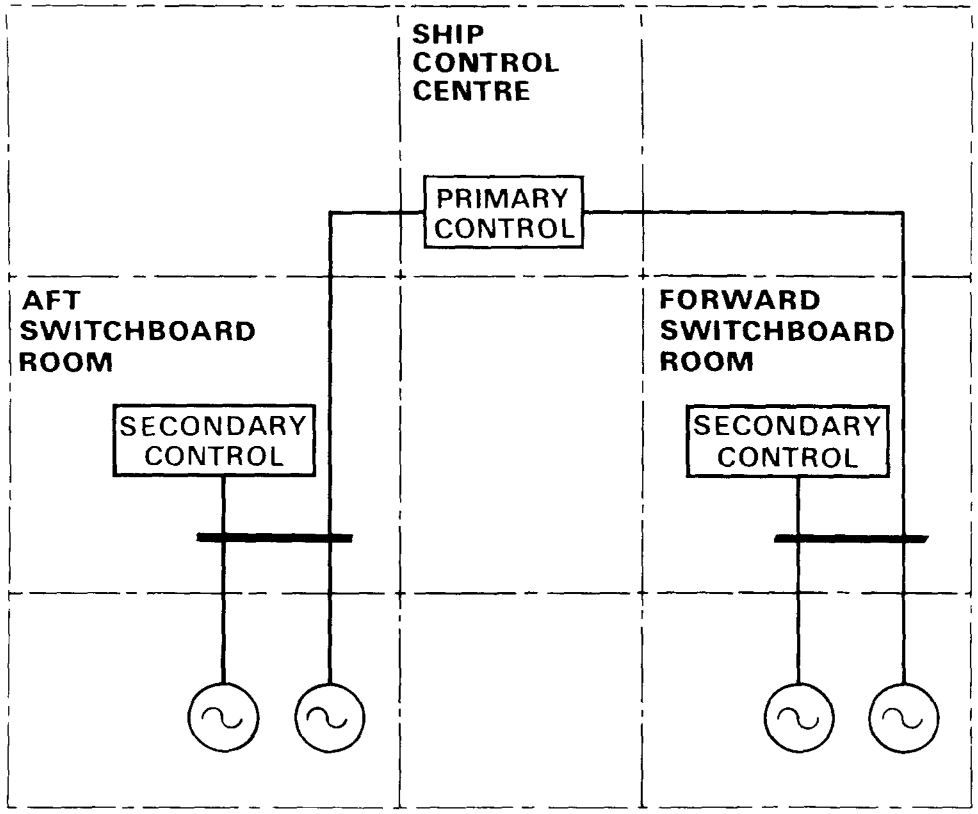

FIG. 9—MAIN SUPPLY SYSTEM CONTROL

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 with other switchboards.

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, 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.

(*a*) *Voltage*

Nominal voltage	440
Load range tolerance	
(*i*) Average line-to-line value of 3-phase system	±5%
(*ii*) 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)	
(*i*) Frequent transients (10 times per hour)	+6% −10%
Recovery time 0·5 seconds.	
(*ii*) Infrequent transients (10 times per 24 hours)	+10% −15%
Recovery time 1·0 seconds.	
(*iii*) 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.

(*b*) *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) Recovery time 2 seconds.	±3·75%
Rare transients	+12% −10%
Recovery time 6 seconds.	

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

(*c*) *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 ships' 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 systems, 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.

Electromagnetic Interference

With the large number of systems and closely bunched cable runs, together with tightly packaged miniature electronic equipment, it must be assumed that Electromagnetic Interference (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.[7] 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.

Converted Supplies

Although the main supply and distribution system is one of the most important systems in a Royal Navy warship, there are numerous other electrical systems derived from the main supply system. These are defined as converted supplies, and 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.

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.

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 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 the declared NATO aim as defined in STANAG 1008,[4] namely: 'equipment is not to be designed to operarte on a converted supply if 440 volts 60 Hz will suffice'. This policy is 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 wave form, 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:

(*a*) *Float:* Pumping and fire-fighting equipment; lighting and internal communications; and flood alarms.

(*b*) *Move:* Auxiliary services to main propulsion units and control of main propulsion and steering; plus sick-bay facilities.

(*c*) *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, to where they are finally connected to the important load.

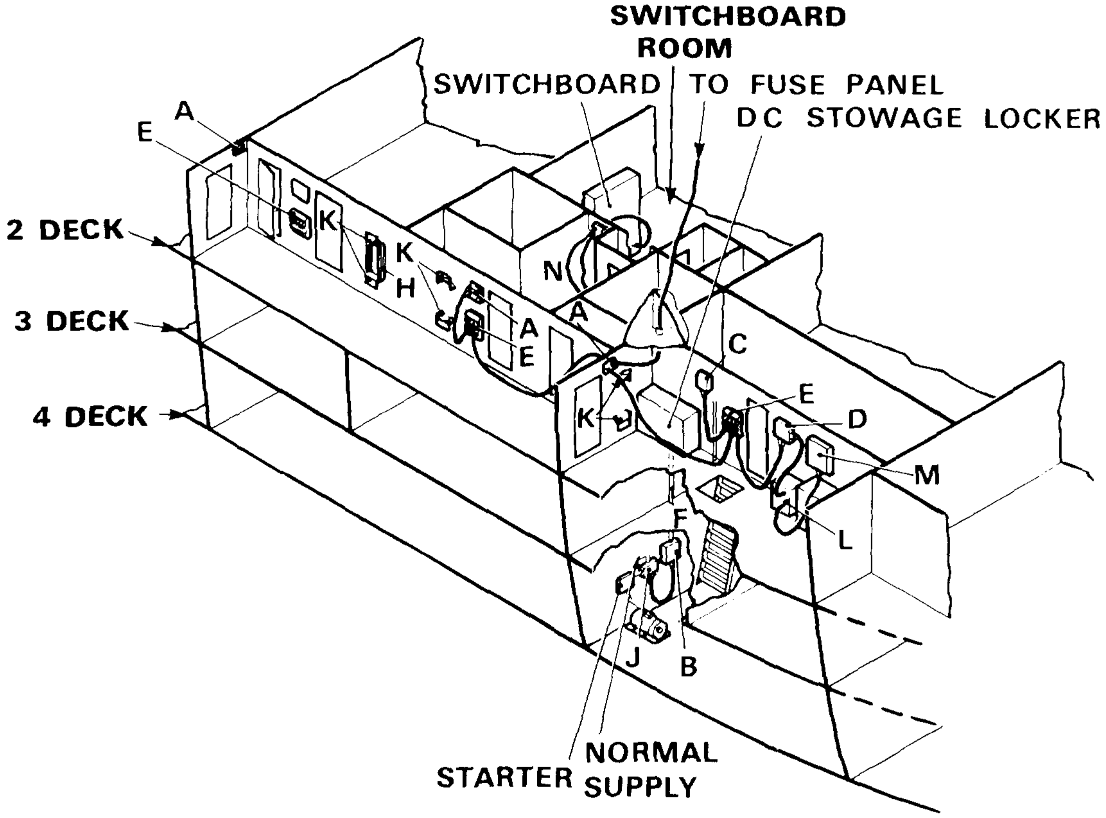

Fig. 10—Typical emergency supply system

A: through-bulkhead terminal
B: riser connection—top entry
C: riser connection—bottom entry
D: portable fuse box
E: portable link box
F: deck tube for permanent cables
G: deck tube for emergency cables
H: emergency cable sockets
J: emergency change-over switch
K: emergency cable stowage bracket
L: portable 440/110V transformer
M: 115V portable fuse panel
N: emergency cable

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

TABLE III—*Conductor insulation*

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

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 R.N. 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 tonne ship, the cables weigh 118 tonnes and the associated support system and glanding another 23 tonnes. 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 majoirity 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 tonnes, which can be invaluable to the naval architects for the 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 and 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 and size advantage is indicated in FIGS. 11, 12, and 13 (although there is less difference in overall cable sizes, as insulation is a constant thickness). If the CSA is reduced too far then volt drop considerations prevail.

Cable Sizing Selection

In selection of cable sizes for generation and distribution, due care must be taken and reference made to existing policy on installation (NES 513 and NES 502)[5,6]. This is best appreciated by reference to FIG. 14, which enables a cable size to be determined in 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 intrinsic shortcomings, namely:

(*a*) Information to operators and maintainers is limited in scope and is only available at the switchboards.

(*b*) Operation of the system requires a high degree of skill.

(*c*) Load balance between the generator and switchboard is very difficult to achieve with a split-system design.

(*d*) Prolonged light loading of diesels during action stations or exercise.

(*e*) Limited duplication of supplies to users.

(*f*) Total manual operation; hence high training load and risk of 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 are 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 prone to errors or where speed of response is critical.

An additional advantage of the proposed method of implementation is the provision of additional plant information, to enable incipient plant failures to be recognized. This links 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 have 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. Functionally, the main supply system can now be considered as one of the

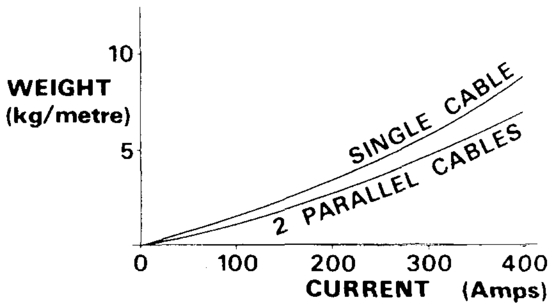

FIG. 11—SINGLE VERSUS PARALLEL CABLES: CURRENT/WEIGHT

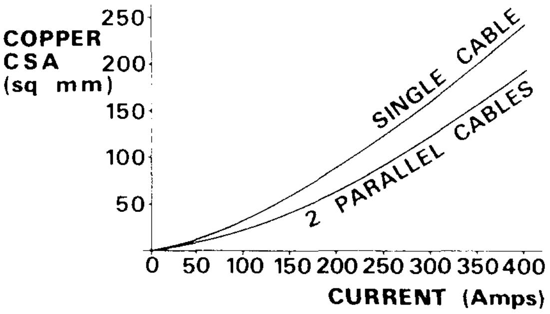

FIG. 12—SINGLE VERSUS PARALLEL CABLES: CURRENT/CONDUCTOR CROSS-SECTIONAL AREA

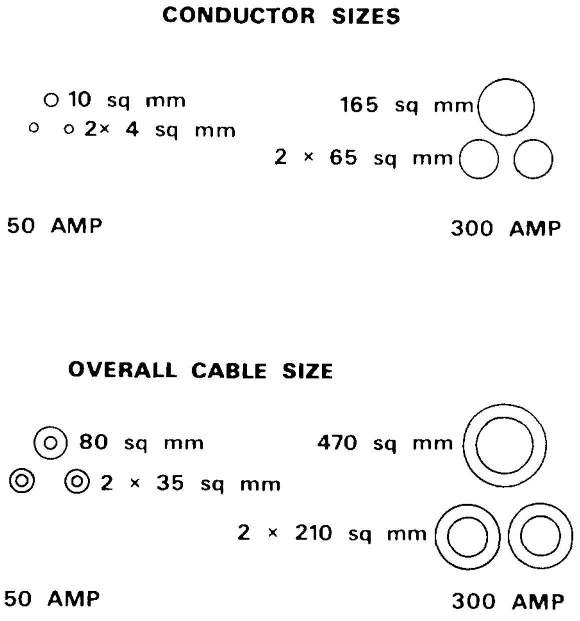

FIG. 13—SINGLE VERSUS PARALLEL CABLES: CABLE SIZE

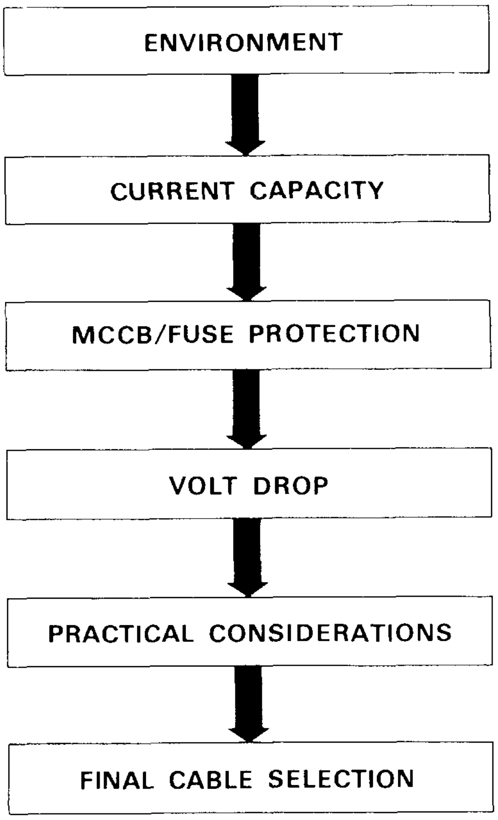

FIG. 14—CONSTRAINTS ON CABLE SELECTION

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.

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.

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