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ELECTRICAL DESIGN CONCEPTS AND PHILOSOPHY FOR AN EMERGENCY AND SUPPORT VESSEL

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Electrical Design Concepts and Philosophy for an Emergency and Support Vessel

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SYNOPSIS

An emergency and support vessel (ESV) is a multi-functional vessel whose principal role is to assist offshore platforms in case of unforeseen difficulties or disaster. Iolair *is the first ESV purpose-built for British Petroleum and the British National Oil Corporation. The first concepts of* Iolair *were beginning to take shape in the Shipping Department of BP in late 1975. The vessel is a semi-submersible having two pontoons supporting a platform superstructure on six vertical columns. Diesel electric generation provides power for propulsion and all services. Transit speeds of up to 12 knots are anticipated using the main propellers driven by twin geared induction motors. These, in combination with tunnel thrusters located forward and aft in each pontoon, give substantial dynamic positioning capability. In addition to its emergency roles,* Iolair *has facilities for routine functions such as: saturation and surface diving; accommodation for transient personnel; maintenance and inspection, and helicopter handling. The vessel and its tasks are discussed in Ref. 1. In the present paper the authors describe the design and philosophy of the electrical systems on* Iolair, *which evolved in conjunction with the machinery and hull designs.*

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INTRODUCTION

The electrical systems for an ESV are necessarily much more extensive and complex than in a conventional merchant vessel, since they are at the heart of every major power or control function. For a multi-role vessel incorporating dynamic positioning (DP) and diving, the security and integrity of both power and control systems are paramount. The design incorporates many features which are novel in marine application and which, in some instances, have been purpose-designed for the application.

A prime consideration was integration of machinery and electrical systems, both with each other and with hull and hotel facilities. This was also carried over into a close co-operation with the leading manufacturers who competed for supply of equipment for the vessel. In this way it was possible to incorporate many of the manufacturers' suggestions and to ensure a fully co-ordinated approach.

The design of *Iolair*'s major systems involved a re-appraisal of traditional marine engineering practices. Each concept was thoroughly examined and its validity verified. However, since the vessel was to be constructed in a shipyard, the introduction of features completely foreign to existing practices could have invited extended delivery periods and prohibitive costs.

To ensure maximum security, the essential services are provided with a high degree of both physical and electrical segregation. The siting and method of supply to equipment are arranged to maintain maximum effectiveness under fault or damage conditions. Essential items of equipment are duplicated and supplied from different sources and by different routes. The structural design of the vessel facilitates this philosophy but it has been extended to segregation of generating plant, transformers and control. In this respect, the original ESV concept anticipated the DOE (Department of Energy) *Guidelines for Dynamically Positioned Diving Support Vessels*[2] by several years.

The system is arranged so that full operational capability can be maintained in the event of either loss of the machinery control room (MCR), including the main medium tension (MT) 415 V switchboard, or loss of the standby switchboard.

Reduced, but effective, propulsive and side thrust and fire-fighting capability can be maintained in the event of loss of any one of the following:

Engine room;
Machinery space;
Section of the high tension (HT) 6600 V switchboard;
Supplies through a column (leg) of the vessel;
Group of segregated cables.

The principal machinery control station is the MCR which contains the main MT switchboard, setting-up console, and manoeuvring and alarm console. The central alarm monitoring system and manual control of propeller pitch are part of the manoeuvring console function. A mimic diagram of the electrical system, with instrumentation and control, forms part of the setting-up console.

There are local control centres in all main machinery spaces. They incorporate main section boards, secondary alarms, communications facilities and other specialized features.

In an emergency, the design requirement is that *Iolair* be capable of withdrawal from potentially hazardous gas concentrations. This has made a significant impact on the design of the electrical system, since the areas designated as potentially hazardous include all exterior vessel surfaces and structures above the waterline; and ventilation inlets and plenum chambers, air locks and all areas having direct access to decks unless airlocked or having gastight shutdown flaps.

To achieve this requirement, certain sections of the electrical system can be remotely tripped from a damage control console on the control bridge and are locked off prior to the vessel undertaking a jeopardous role. Essential circuits and equipment, which must remain operational during these activities and which are sited in the potentially hazardous areas, are designed and certified for BS5345 Zone 2 Gas Groups II A and II B with T3 temperature classification. Additionally, any such equipment installed on weather decks is watertight. The status of ventilation closures and airlock doors is indicated on mimic diagrams in the damage control console on the control bridge and in the MCR.

PRIMARY GENERATION AND DISTRIBUTION

HT Power system design

The HT system of the vessel is depicted in Fig. 1 and the following services are connected to the HT switchboard:

Six diesel generators (3.4 MW, 4 MVA, 6-pole)
Two propulsion motors (2.24 MW, 4-pole)
Two propulsion/fire pump motors (2.24 MW, 4-pole)
Two fire pump motors (2.24 MW, 4-pole)
Four thruster motors (1.5 MW, 6-pole)
Three HT/MT transformers (2.25 MVA)
Two electrode boiler transformers (1.2 MVA)

A 6.6 kV, 50 Hz, three-phase, three-wire insulated neutral system is used. The switchboard is arranged in three sections electrically. Two bus-section breakers connect a centre section to two flanking sections and are closed in normal service. A further bus-section breaker may be closed to connect the two flanking sections but is interlocked open in normal service. The fault rating of the HT switchboard and cabling allows for the contribution of all generators, motors and transformers.

The entire HT system is designed to withstand or inhibit, without injurious effect, any overvoltages which may occur. Similarly, the system insulation is capable of withstanding any earth fault for a period of at least 24 hours at one time and for at least 200 hours in each year.

System insulation

Traditionally, medium-voltage marine installations operate with an insulated neutral system. The mechanical strength needed for the insulation more than adequately covers the electrical requirements. For higher voltage systems, an examination of alternative neutral point systems is required. These are:

Solid earthing;
Reactance (resonance) earthing;
Resistance earthing;
Unearthed system.

An appreciation of their respective advantages and disadvantages is necessary to select the correct system to suit the application.

Solid earthing

This system can be defined as being solidly earthed through an adequate connection in which no impedance has been inserted intentionally. An earth fault results in the flow of large currents which must be cleared. This is achieved by isolating the affected circuit.

Reactance (resonance) earthing

This is earthing via a reactance of such a value that, during a fault at rated frequency between one of the conductors and earth, current flowing in the earthing reactance substantially equals the capacitive current flowing between the unfaulted conductors and earth.

Resonance earthing removes the problem of overvoltages caused by arcing earth faults. However, a voltage rise of 1.73 times the normal value will occur on the remaining phases if one phase has a permanent earth fault. If the insulation is not adequate, other faults may occur. This system does not lend itself to multi-machine marine installations because of variations in connected plant.

Tuning of the reactance, as well as the necessity to ensure that it is in circuit, can be critical.

Resistance earthing

This method is similar to the resonance earthing method, where the resistance is chosen to take a current equal to that of the system capacitance.

This system is even more critical with respect to matching the resistance and capacitance. It also has the disadvantage of large resistors with consequent heat dissipation.

Unearthed system

This method has the advantage of continuing to operate with one earth fault on the system. However, the disadvantages under fault conditions are:

(a) A solid line-to-earth fault; this will raise the electrical stress on the two healthy conductors from phase voltage to line voltage. Hence, the system must be capable of sustaining this voltage.

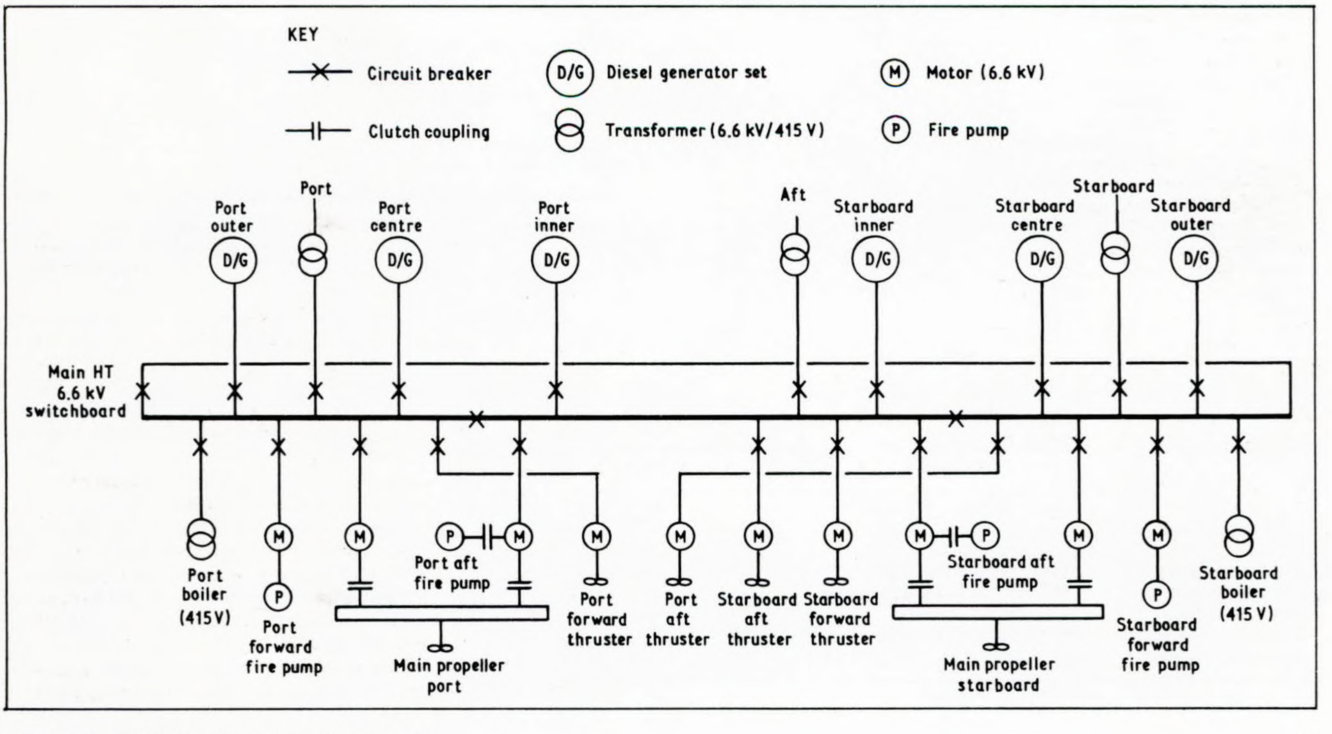
(b) Arcing earth faults: these have been the subject of many studies and papers.[3–9] It is generally accepted that they are likely to occur if the capacitive current of the system is greater than 5 A. This value can be calculated from the simplified expression of:

$$I_f = \frac{\sqrt{3}E_L}{X}$$

where I_f is the fault current; X is the leakage reactance per phase, and E_L is the line-to-line voltage.

To avoid the overvoltages associated with arcing faults, the capacitance of the system has to be less than 1.392 μF for a 6.6 kV

FIG 1 Schematic of HT system



system. Values obtained for the system described are shown in Table I.

(c) Overvoltages: these occur due to the creation of resonant combinations of system capacitance, resistance and reactance in series or parallel paths to earth under fault conditions.

From calculations of the installation parameters for *Iolair*, it was determined that the arcing earth fault criteria were not met and, although the overvoltage phenomenon could occur, the installation was heavily damped; and equipment insulation levels were sufficient to alleviate this problem, with the aid of suppression equipment on motor and transformer circuit breakers.

The unearthed system offered the most flexible approach whilst retaining operation of plant in the event of a single earth fault. Security of plant, which is essential for an ESV, was thus achieved without the need for extra equipment. Generators can be automatically connected to meet load requirements. There is then no need for concern that, if the system develops an earth fault, it will be isolated by switching actions.

Propulsion machinery considerations

It is essential that machine insulation, both to earth and between turns, is of the highest specification. *Iolair*'s machinery is designed to withstand a voltage surge of 31 kV. This means that winding insulation will last for a design life of at least 20 000 switching operations with current chopping and multiple re-ignition at maximum levels.

Margins of safety were built in by assuming current chopping at 10 A. This gave peak surges of 15 kV and 10 kV for the thruster motors and propulsion motors respectively. Actual current chopping by the vacuum interrupters in service is not expected to exceed 5 A; and surge diverters to operate at levels in excess of 20 kV are fitted to switchgear for consumers.

Guaranteed performance figures for rotating plant were demanded. This is perhaps unusual for marine electrical installations but for *Iolair* it was considered to be crucial, particularly in respect of power factors of the major load consumers. A nominal system power factor of 0.85 was selected for the purpose of rating the HT generators. Based on the guaranteed performance data (Table II), calculations were made for various load conditions to show that, for the proposed generator active load in sequential starting conditions, the reactive load would be within acceptable limits. Examples are shown in in Fig. 2.

During works tests, the performances of all machines were demonstrated to be better than the guaranteed figures, particularly the light load power factors of motors.

In the event of two propulsion motors driving the one propeller at full pitch, it is necessary to ensure that loss of one motor does not cause the other to stall. The pull-out torque is therefore greater than 210% rated torque. Load sharing between two motors at similar temperature will be within ±2.5% of the average value at all loads.

All motors, when switched direct-on-line, develop more than 50% of full-load torque to ensure adequate acceleration. Although starting is normally carried out with at least four generators operating in parallel, it is also required that two generators be capable of starting a propulsion motor. Starting kVA is limited to 13 500 and, in normal circumstances, the transient voltage dip is rather less than 15% of nominal voltage.

Generators and motors are fitted with sleeve bearings, those of the propulsion and fire pump motors being flood lubricated and the remainder self-lubricated. If the flood lubrication supply failed, the bearings were required to have sufficient self-lubrication to sustain up to 15 min of further operation without damage. Judging by the works test results, the self-lubrication capabilities of these machines would probably suffice for all conditions. Bearings are also provided with both metal and oil temperature monitoring.

The HT machines on *Iolair* all have a closed air circuit and are water-cooled, with double tube coolers and leakage detection facilities. Generator cooling circuits have quick-release doors for emergency ventilation, permitting continued operation at full rated output. No similar facilities are provided for the propulsion and thruster motors as this would cause ventilation difficulties in the relatively small compartments in which they are sited.

Phase segregated main terminal boxes are fitted to all machines while separate neutral terminal boxes house differential protection current transformers (ct's).

The automatic voltage regulators and de-excitation equipments for the generators are accommodated in the HT switchboard, as are rotating diode failure detectors which give an alarm on sensing this fault.

Table I: 6.6 kV system capacitances to ground per phase of HT machines and cables (total capacitance 1.371 μF)

PLANT	CAPACITANCE (nF) Plant	CAPACITANCE (nF) Cable
Main generator port outboard	83	10.56
Main generator port centre	83	9.9
Main generator port inboard	83	10.12
Main generator starboard inboard	83	7.92
Main generator starboard centre	83	10.34
Main generator starboard outboard	83	11
Electrode boiler port		5.28
Main transformer port		10.56
Port forward fire pump motor	54	16.06
Port inboard propulsion motor	54	26.18
Port forward thruster motor	56	18.04
Port outboard prop–fire pump motor	54	23.54
Starboard aft thruster motor	56	21.78
Starboard forward thruster motor	56	25.96
Starboard outboard prop–fire pump motor	54	21.56
Main transformer aft		12.76
Port aft thruster motor	56	26.4
Starboard inboard prop motor	54	25.08
Starboard forward fire pump	54	16.94
Main transformer starboard		9.9
Electrode boiler starboard		5.06

Table II: Guaranteed performance data

PLANT	EFFICIENCY (%) Full load	¾ load	½ load	¼ load	POWER FACTOR Full load	¾ load	½ load	¼ load
Main generators	96.6	96.4	95.9	—	0.85	0.85	0.85	—
Standby generator	94.3	93.75	92.5	—	0.8	0.8	0.8	—
Propulsion/fire pump motors	96.6	96.6	96.2	94.1	0.9	0.9	0.86	0.71
Thruster motors	96	95.9	95.3	92.7	0.86	0.83	0.76	0.55

Note: ¼ load figures not guaranteed to BS tolerances.

High-voltage transformers

The following alternative types of transformer were examined for their suitability:

Open air cooled, class 'C' insulated.
Sealed nitrogen filled, class 'C' insulated.
Askarel filled.
Silicon filled.
Cast resin insulation.
Water-cooled type, class 'C' insulation.

In selecting the transformers, the following factors were considered:

1. Space in the vessel was at a premium and free access had to be achieved.
2. Insulation contamination.
3. Vibration.
4. Possible pollution due to leakage of insulating or cooling agents.
5. Toxicity and flammability of the insulating or cooling agent in its natural state or when subjected to arcing faults.
6. Operating experience.

The nitrogen-filled, class 'C' insulated transformer was chosen as being the best suited to meet the above considerations.

The transformers are constructed of a class 'C' insulation winding contained within a steel tank. The tank is charged with nitrogen: this acts as a coolant; inhibits burning; and gives a longer insulation life and higher overload capacity. Instead of cooling radiators the transformer has a system of cooling tubes which pass through the tank and allow air flow from bottom to top. As a result of works tests, the transformers were modified to include fans, which maintain the air flow through these pipes whenever the transformers are energized.

Terminal boxes are fully phase-segregated to prevent flash-overs between phases. The transformer manufacturers originally misinterpreted this requirement because they were not aware of any industry-wide definition. The only standard laid down for phase segregation applies to machines and not to other electrical plant.[10]

No tapchanger is provided as would be expected on a land-based transformer of similar size. The medium-voltage system can float with the regulation of the transformer over its load range. The maximum drop is 20 V when the transformers are fully loaded. Normally they operate at approximately half load. A primary voltage surge of 55 kV can be experienced without causing any injurious effects; and the winding temperature and pressure of the nitrogen are monitored. An added advantage of this type of transformer is its ability to continue to operate, albeit at a reduced capacity, with a total loss of nitrogen from the tank.

Table III: Types of protection used on HT system

GENERATOR	MOTORS		
Bias differential Reverse power IDMT overcurrent Short circuit (delayed) Under/overvoltage Excitation fault Diode failure	Single phasing Bias differential Short-circuit (instantaneous) IDMT overcurrent Undervoltage	Bias differential Short-circuit (instantaneous) Undervoltage Intertripping with MT	Directional short-circuit

High-voltage cable

HT cables are constructed as single core, tinned copper conductor; semi-conducting tape; ethylene propylene rubber (EPR) insulation; chlorosulphonated polyethylene (CSP) sheath; tinned phosphor bronze braid, with an overall CSP sheath. Cable design is based on BS6883[11] but the conductors are to BS6360[12] and the insulation and sheathing materials are to BS6899.[13] The highest rating covered by BS6883 being 3.3/3.3 kV, it was necessary to establish insulation thickness by reference to BS7-1953[14] which covers cables up to 11 kV with earthed neutral, i.e. 6.35/11 kV grade.

Aluminium cables were also considered. In general, for an equivalent current rating, there is a weight saving of 15 to 20% but this is reduced because fittings are heavier. Since no other significant benefits could be identified, aluminium cables were not chosen.

The cable initially selected for the installation was not intended to have an overall CSP sheath, and the phosphor bronze braid was to be earthed at all points of clipping. This was changed because of anticipated difficulties during installation of ensuring an effective earth at every clip and of handling a cable without an overall sheath.

The justification for this change was based upon calculations of the potential gradient that could exist with earthing of the braid only at the extremities of the longest cable run envisaged. The calculations of this gradient gave a value of 6.3 mV.

The extra CSP sheath enhances corrosion resistance and has been given a distinctive pink colour to distinguish it from all other cables. The shipyard may not paint over any of the high-voltage cable and the colouring has helped to ensure this.

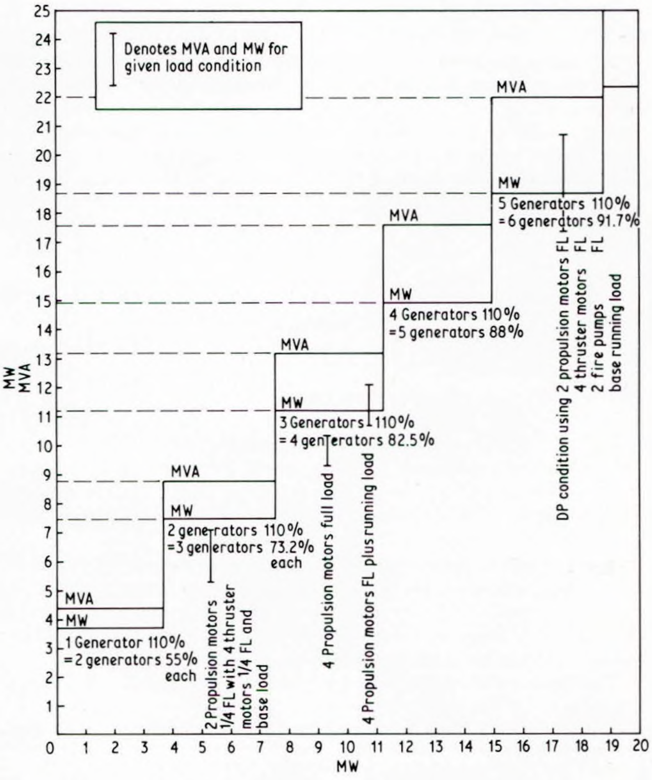


FIG 2 Comparison of MW and MVA loadings with ship's load and MW–MVA limits for the loss of one engine

HT Switchboard

Vacuum interruptors were adopted for the 6.6 kV switchgear prior to their general approval by Lloyd's Register of Shipping for use on ships. Interruptors were selected for all feeder circuits as well as for generator and bus-section circuits, although in many instances it would have been possible to utilize vacuum contactors. The principal advantages of the final selection were lower first cost, low weight, minimum length, frequent switching capability and low maintenance stemming from simplicity of design.

In normal service, switching operations are carried out from the MCR setting-up console. The designed security of *Iolair* required that the HT switchboard rooms formed a secondary control centre, resulting in an unusually high degree of segregation for circuits and equipment.

Duplication of instrumentation and essential controls at either location caused severe difficulties in panel layout and accessible terminal locations. Synchronizing at the switchboard is facilitated by the use of trolleys with 'plug-in' connections. These trolleys must be used for synchronizing across bus-sections, since closing of these breakers can only be carried out at the switchboard.

The busbars are carried through the bulkhead between the two switchboard rooms by specially adapted fire-retardant bushings enclosed in a protective trunking. The two switchboard rooms are completely fire segregated, both from each other and from adjacent compartments.

SYSTEM INTERACTIONS

Protection

The electrical protection system on *Iolair* consists of high- and medium-voltage sections, with interfaces for discrimination and the transition from one voltage to another.

The medium- and lower-voltage protection is of a type common to most vessels, being reverse-power, overcurrent, and relay operated or 'direct' short circuit tripping.

The high-voltage system's protection is common to land-based installations but is novel in marine practice. Types of protection are given in Table III.

Reasons for selection of these types of protection were:

- The bias differential protection is zonal and ensures isolation of faults at an early stage to minimize undue damage.
- The use of the inverse definite minimum time (IDMT) overcurrent protection allows maximum use of the overload capacity of machines, whilst retaining a high degree of protection. This is particularly desirable for propulsive units.
- The directional protection used on the bus-section circuit breakers stems from the high-voltage busbar system having an open ring configuration and the need to isolate only that section of the busbars which is directly affected by the fault.
- The directional short circuit protection is worth further examination. It consists of a duplicated combination of a directional relay

and an IDMT current relay (Fig. 3). Each combined unit protects against short circuit current flowing through the bus-section but senses opposite directions of current flow.

The operation is as follows:

1. The directional relay has voltage and current coils which exert a torque on a cup contact within the relay if the voltage and current are outside set phase-angle limits. This torque is proportional to the chosen direction of three-phase power flowing and the cup contact is still operative with the voltage falling to 1% of normal. This cup contact is used to arm an IDMT relay which performs the protective tripping.
2. The IDMT relay used is basically an induction disc relay which is operated by a shading coil; which, itself, is armed by a fall in busbar voltage to 30% of normal. The relay used is modified from the standard unit and has only short circuit characteristics.

Although this protection unit appears complex, it allows discrimination between other bus-section circuit breakers by time and direction of current; as well as with the generators on current and time; and with the high-voltage motors on undervoltage and time. This is shown on one of the protection diagrams, illustrated in Fig. 4. An interesting effect of the undervoltage grading of the system was the need to delay the tripping operation of the MT circuit breaker no-volt coils to allow a short circuit on the HT system to clear. This was necessary to gain time for the essential service starters to operate in their intended fashion.

The keystone of the power systems philosophy for the vessel is to minimize the possibility of complete power failure. Thus, however serious an equipment or system fault, the protective measures must identify and isolate the affected areas so that the remaining plant may continue operating without interruption.

It is therefore unusual that there are no facilities for automatic restart of essential services after sustained blackout. This deliberate design feature recognizes that the system protection is so comprehensive that a fault serious enough to cause blackout will in any case require operator intervention to re-establish the plant in operation and to assess the extent of its further capabilities.

A fault of short duration (such as a major short circuit) is, however, coped with automatically. Delayed undervoltage protection inhibits tripping of healthy HT consuming plant, whilst special electronic relays in each 415 V essential service starter times the duration of the suppressed-voltage or blackout condition.

The equipment response is programmed accordingly. Contactor drop-off response is slugged so that, for faults up to 0.2 second duration, the contactor will not open. Durations between 0.2 and 4 seconds would cause the motors to stall and a sequential restart is programmed for this condition.

For a fault duration beyond 4 seconds it was anticipated that the main engines would shut down through sustained cumulative loss of services; thus, no re-starts are initiated. Standby essential services are similarly programmed.

The responses of all important plant to these conditions were fully checked and confirmed during the computer stability analysis of the system. The settings chosen depend on both the plant characteristics and the grading of upstream protection.

Full co-ordination of protection, right through from 415 V feeders to 6.6 kV main generators, including bus zone protection, was not easy to achieve. The MT and HT switchgear manufacturers are separately to be congratulated for their success. Even more to be congratulated is the shipyard electrical contractor for sustaining the effort to make the manufacturers get it right.

System stability and fault analysis

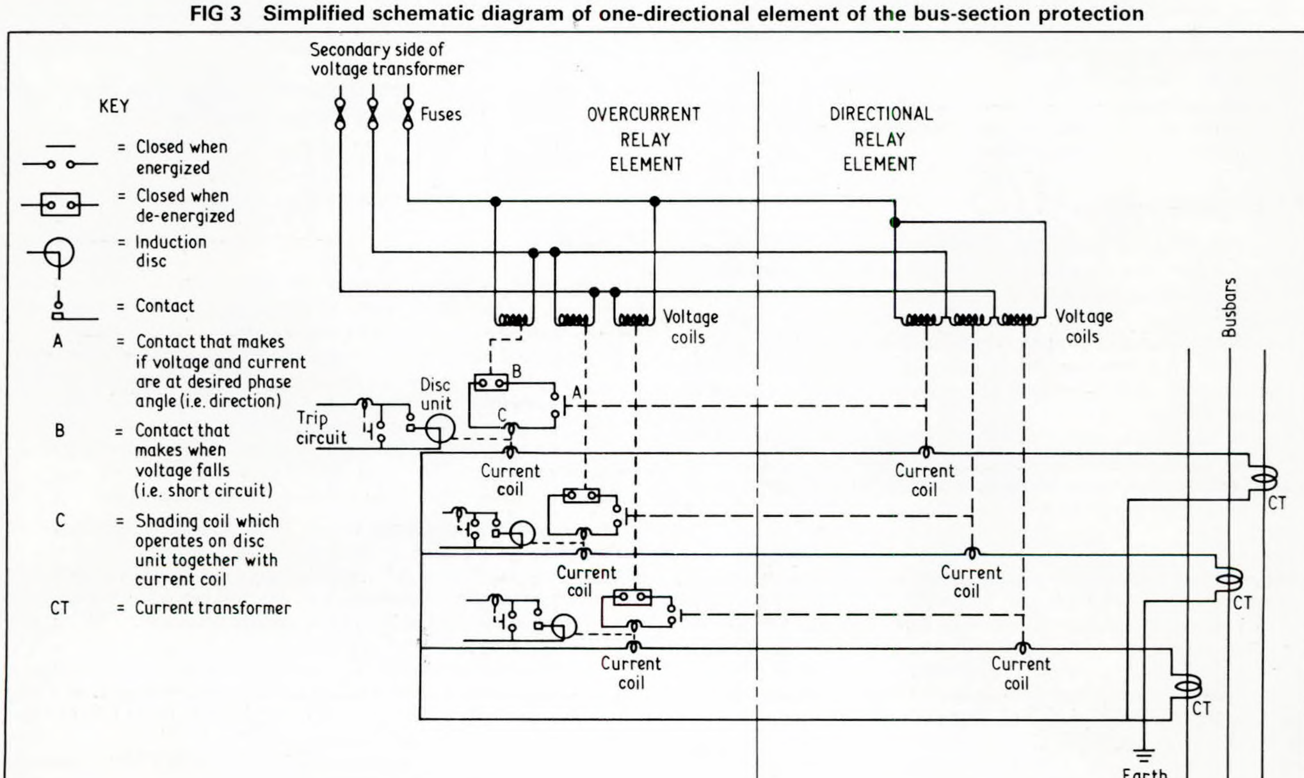
As the design of *Iolair* progressed, it became clear that a dynamic analysis of the power system should be carried out with the aid of a computer. This was to ensure that the whole system (mechanical and electrical) was stable and functioned in accordance with design philosophy in both normal and fault conditons. An inherently unstable power system will result in uncertainties and difficulties in the vessel's operation; conversely, an overdamped power system will not provide the response rates required for adequate performance.

To find the optimum performance condition it is necessary to model the whole system and have the ability to examine the effects of individual components and of the sub-systems of which they are part, in normal and fault conditions. In addition to examining the design characteristics of components and their suitability for meeting the optimum performance requirement, it was also necessary to anticipate changes due to ageing and wear, and acceptable tolerances to maintain performance levels.

Possible causes of instability which were examined are:

Coupling and shaft stiffnesses (torsional and axial).
Rates of response of control loops.
Hunting, due to: governor control, automatic voltage regulator, pitch control or control system (linkage and response).

FIG 3 Simplified schematic diagram of one-directional element of the bus-section protection



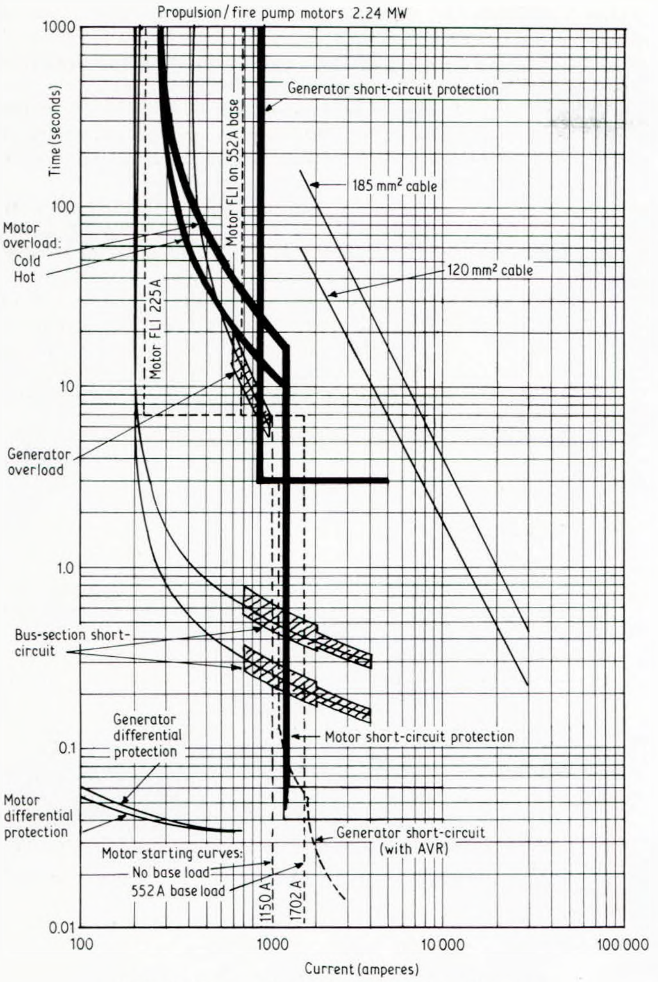


FIG 4 Protection discrimination diagram

System disturbances, such as: short-circuit, overcurrent protection, system interactions, clutch slipping, load switching and frequency control.

These factors may promote 'power swing' or load oscillations between diesel sets or between large motors, which could build up to such values that generators trip and synchronization of the incoming sets is impossible.

The study itself[1,15] was performed in two stages: the first being to examine individual sub-systems and components; the second to look at the overall performance under normal and fault conditions with sub-systems connected together, to see their cumulative effects. An example of the usefulness of the first stage was the confirmation of the specification for the propulsion motor couplings which gave the best torsional results. Similarly, the second-stage study demonstrated that one propulsion motor could be started satisfactorily on two main diesel engines (see Fig. 5) and highlighted the critical time of clearing a fault on the high-voltage busbars to achieve recovery of the system.

Short-circuit calculations

The philosophy determining the short-circuit rating of the equipment to be used on the vessel stemmed from the following factors:

(a) The extent of the electrical network is much greater than on conventional vessels and, using the approximate fault level calculations frequently employed by shipbuilders, could lead to substantial errors in cost estimates.

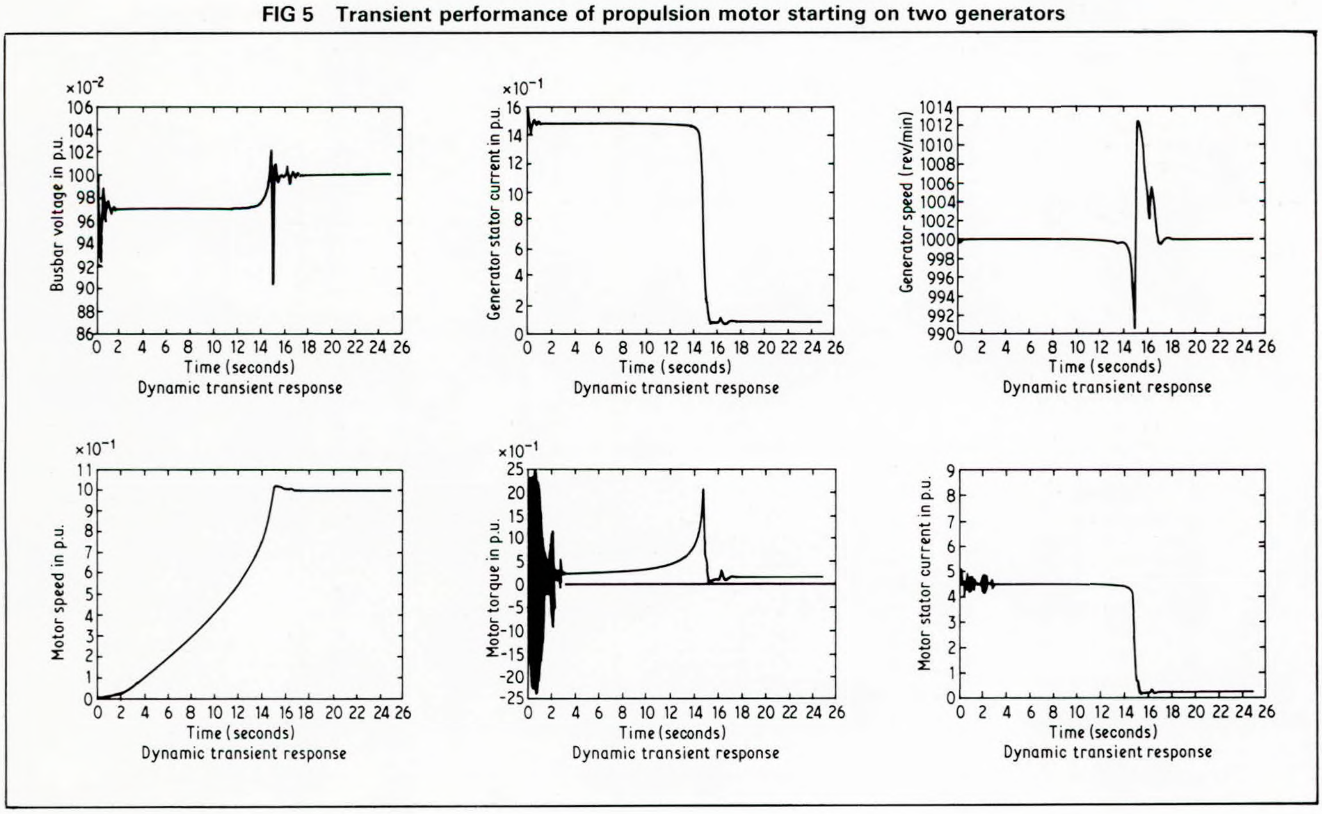
(b) Further, the grading of system protection on large installations depends on accurate calculations correct for the time constants of the network so that components and protection relays can be determined at an early stage.

(c) The safe design of the vessel can depend on detailed calculations.

For the reasons outlined, it was decided to base the method of fault calculations on those given by International Electrotechnical Commission (IEC) Publication 363.[16] The merits of using this method first require consideration of alternative methods, given in BS3659[17] and BS4752,[18] and the allowances, and assumptions, incorporated in them.

Peak fault current is usually assumed to consist of one alternating and symmetrical component and another of direct current. Its attenuation depends on the time constant and power factor of the connected

FIG 5 Transient performance of propulsion motor starting on two generators



plant. Traditional calculations do not allow for both a.c. and d.c. decrements and thus can give a pessimistic estimate of the fault current that exists. This may result in the use of a circuit breaker with greater fault current capabilities than necessary.

Using IEC 363 requires that generator and motor transient and sub-transient reactances, resistances and time constants are known; although smaller motors can be grouped and represented as a single equivalent motor.

Derivation of the fault current contribution of these equivalent motors is a contentious point, particularly multiplication factors for calculating peak fault currents. More accurate results can be obtained by using test data, as supplied in Ref. 19, and converting these to an impedance for insertion in the calculations. Values of fault current calculated by the IEC 363 method for particular positions in the system are shown in Fig. 6.

Performing these calculations has proved worthwhile, since a number of circuit breakers have been found suitable which otherwise would have been ruled out by using alternative methods. Examples are the main transformer MT circuit breakers and some 2000 A circuits on the MT system, where direct-acting series tripping was used instead of the standard shunt tripping system to raise the fault rating of the breakers.

MT SYSTEM DESIGN

415 Volt distribution

To provide maximum security, the 415 V system is distributed via three principal switchboards as depicted in Fig. 7.

The main MT switchboard has three sections which can be connected by two bus-section circuit breakers. Normally, to limit the fault current, these breakers remain open. Two HT/MT transformers, situated in a room directly below the switchboard, each feed outboard sections. Evenly distributed port and starboard consumer plant is arranged in mirror image on either hand. The centre section has no connected loads but is normally energized from the standby switchboard via interconnector circuit breakers on each board. This improves the ability for closed transition synchronizing of sections when changing over supplies.

Originally, the centre section was directly fed by a third transformer. This was changed, to enhance system security and to aid starting and setting up from dead ship conditions.

The standby switchboard is now energized from the third transformer which is in an adjacent compartment. This switchboard may also

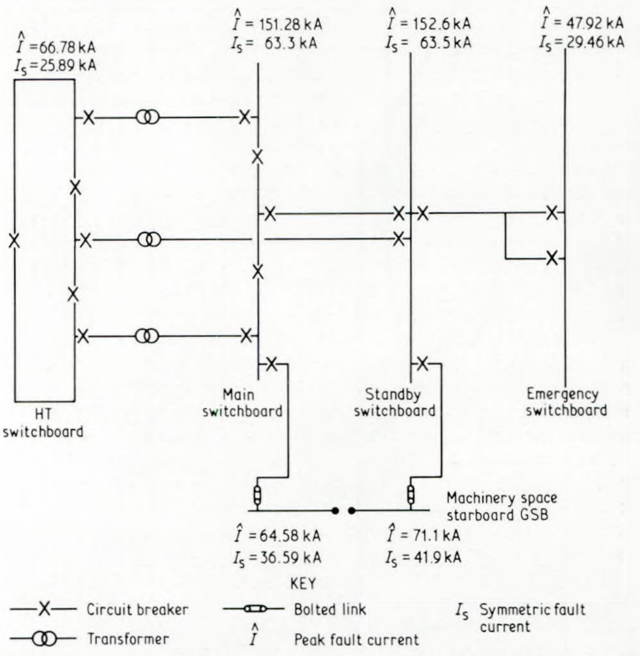
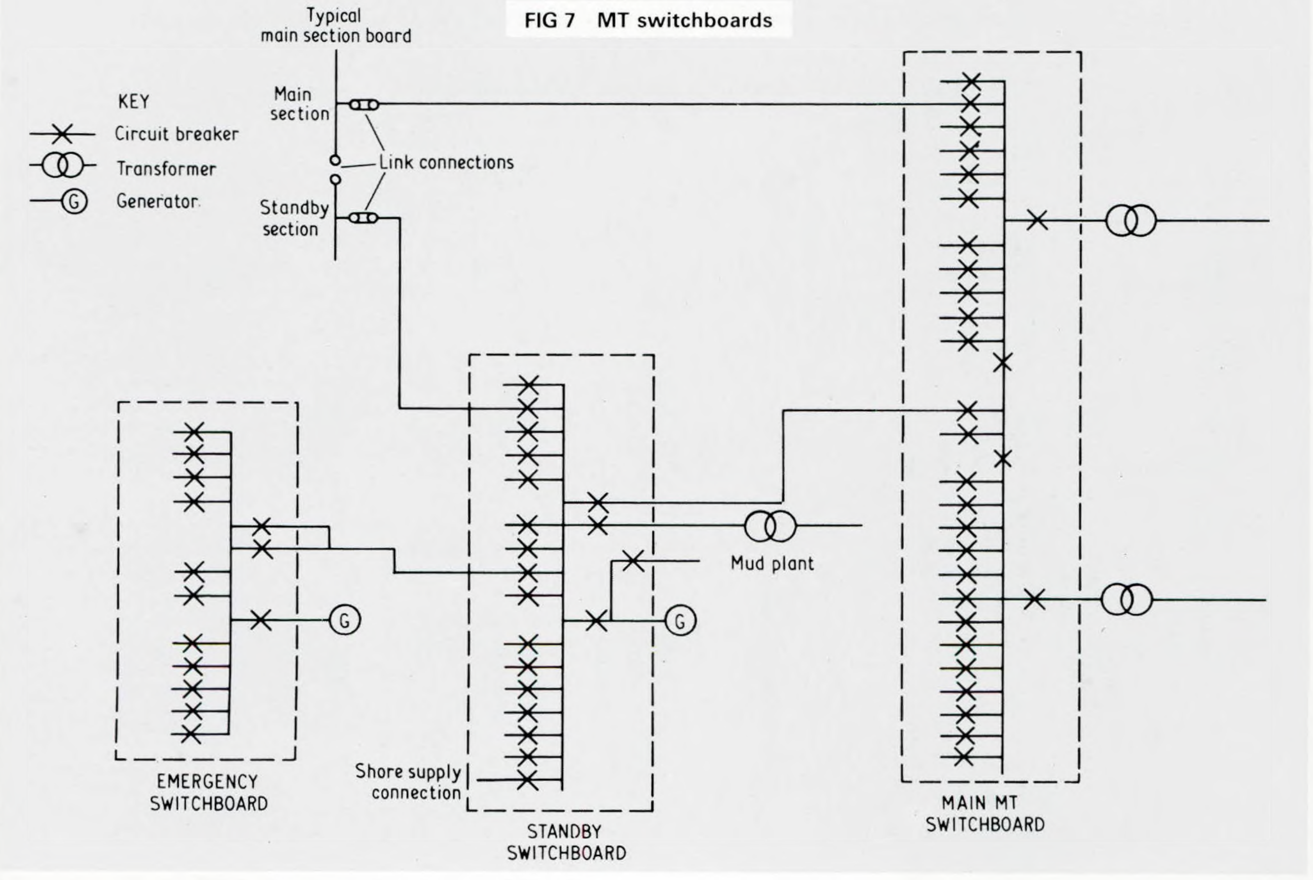


FIG 6 Values of fault current at various points on the distribution system

FIG 7 MT switchboards



be fed by an 800 KW standby diesel generator which can alternatively feed a mud plant switchboard. (Mud plant is provided for a single well-kill operation and will only be used infrequently.) Arranging a normal feeder for this service would have incurred unjustified penalties of increased fault level and cost. The configuration allows a dedicated supply to the mud plant when in use, but gives automatic priority for the standby generator to supply its switchboard if the supply from the transformer is interrupted.

Feeders from the standby switchboard supply duplicate essential service consumer plant to port and starboard. A further interconnector is arranged to the emergency switchboard. Shore supply connections are cabled to a circuit breaker on the standby switchboard.

The emergency switchboard provides statutory and designated emergency supplies, but can also feed back to the standby switchboard when the emergency generator is running.

Under most conditions the MT generators are not required to operate, all MT switchboards being served via the main HT/MT transformers.

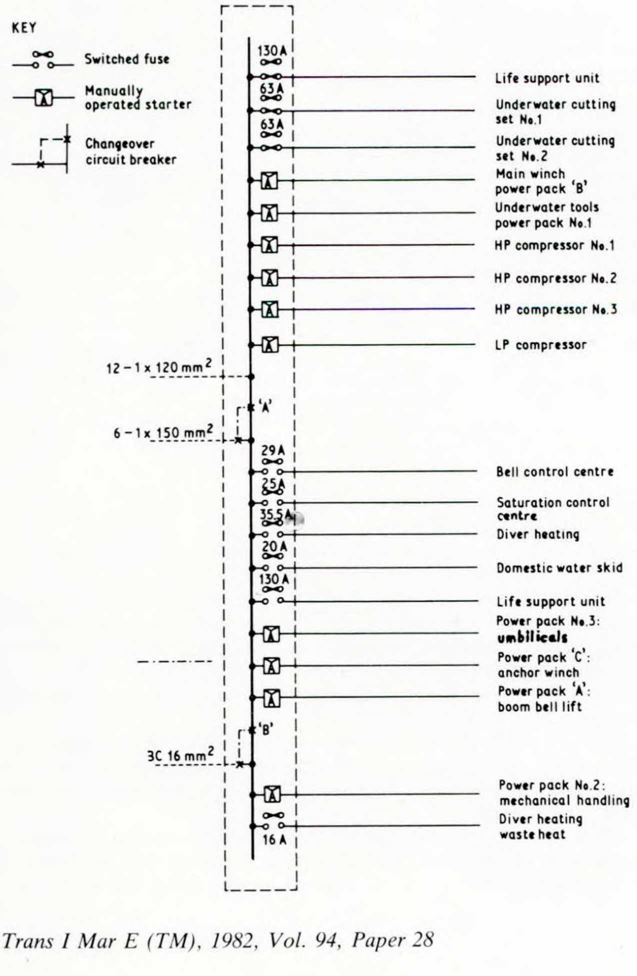
On power failure, the standby generator will immediately start and supply connected loads. After a delay, and if the emergency switchboard has not been energized, the emergency generator starts automatically to restore power.

The diving switchboard is unique on the vessel, since it has direct feeds from main, standby and emergency switchboards. The busbars are in three sections, connected by change-over moulded-case circuit breakers (Fig. 8). Normally all three sections are supplied from the main switchboard feeder, but both the other feeders are live.

Upon supply failure, the first feeder to be re-energized will obtain priority and if this is from the standby switchboard a change-over will occur, isolating the busbar fed from the main switchboard. A similar sequence occurs if the emergency supply is first to be restored. Normal operation is restored manually at operators' convenience.

Precedence of consumer distribution between the three busbars was determined in consultation with the diving equipment contractor. The security established by this system, and by the diving switchboard being of equal construction to other switchboards on the vessel, is considered to set new standards.

FIG 8 Diving switchboard schematic



Galley and laundry earthed system

Galley and laundry services are notorious for earth fault alarms. For this reason, isolating transformers were specified to remove the circuits from the medium-voltage earth leakage monitoring zone, thereby eliminating unnecessary alarms requiring an engineer's attendance. Earthing each secondary side of the transformer permits the use of earth leakage circuit breakers which increase the degree of protection which can be applied. However, earthing of machinery systems, which for operational reasons are required to run even when an earth fault occurs, is undesirable as vessel security is decreased.

The choice of earth leakage protection was governed by:

(i) Sensitivity of trip.
(ii) Fault level if the isolating transformer is bypassed.
(iii) Available supply of equipment.

Authors of papers on the protection of the human body against the effects of electrical shock generally agree that a current of the order of 20 mA (for a period of up to 1 second) has no dangerous effects. Most manufacturers produce two-pole circuit breakers with 10 mA sensitivity and up to 25 A rating but produce three- and four-pole breakers for 30 mA or higher sensitivity.

If either transformer fails, both services can be connected to the remaining unit with suitable precautions or be connected directly to the medium-voltage system. This means that the fault rating of the circuit breakers has had to be increased.

With these constraints, it was decided to utilize moulded-case circuit breakers and separate earth leakage relay. Fifteen milliamperes was thought to be a good compromise between a level at which spurious tripping of the circuits would not cause a problem and a level at which adequate protection would be given to operating personnel.

Group starter boards

Iolair is equipped with some 300 motor-driven units. As far as possible, the circuitry and arrangements of their starters are standardized. Three basic types of starter were selected and controls designed to be interchangeable between types, and flexible within each type. The three types were to provide for:

Manual start/stop only;
Semi-automatic and automatic control for items such as compressors;
Essential services with duplicate automatic standby.

Fault alarm outputs, remote control and indication facilities were incorporated in all starters, so that a final decision as to their use could be deferred if necessary. Terminal arrangements and numbering for remote controls are identical for all types, thus simplifying maintenance and fault finding.

Most motor control gear is accommodated in section boards strategically sited throughout the machinery spaces and frequently incorporating or adjacent to local control centres containing alarm displays, mimic diagrams, communications and monitoring equipment. The communication includes jack plugs for head sets, to aid fault finding between control centres located elsewhere.

Section boards are built to BS5486 and National Appendix Class 3CF[20] and, up to about 90 kW rating, the starters are withdrawable. Section boards, incorporating essential service starters, have two separate busbars to supply the duplicated units, fed independently from the main and standby switchboards. Bolted links in an incoming section permit isolation of feeders and common connection of the two busbars to one feeder, should this become necessary. Feeders are rated to allow some flexibility in these circumstances, and are run by different routes.

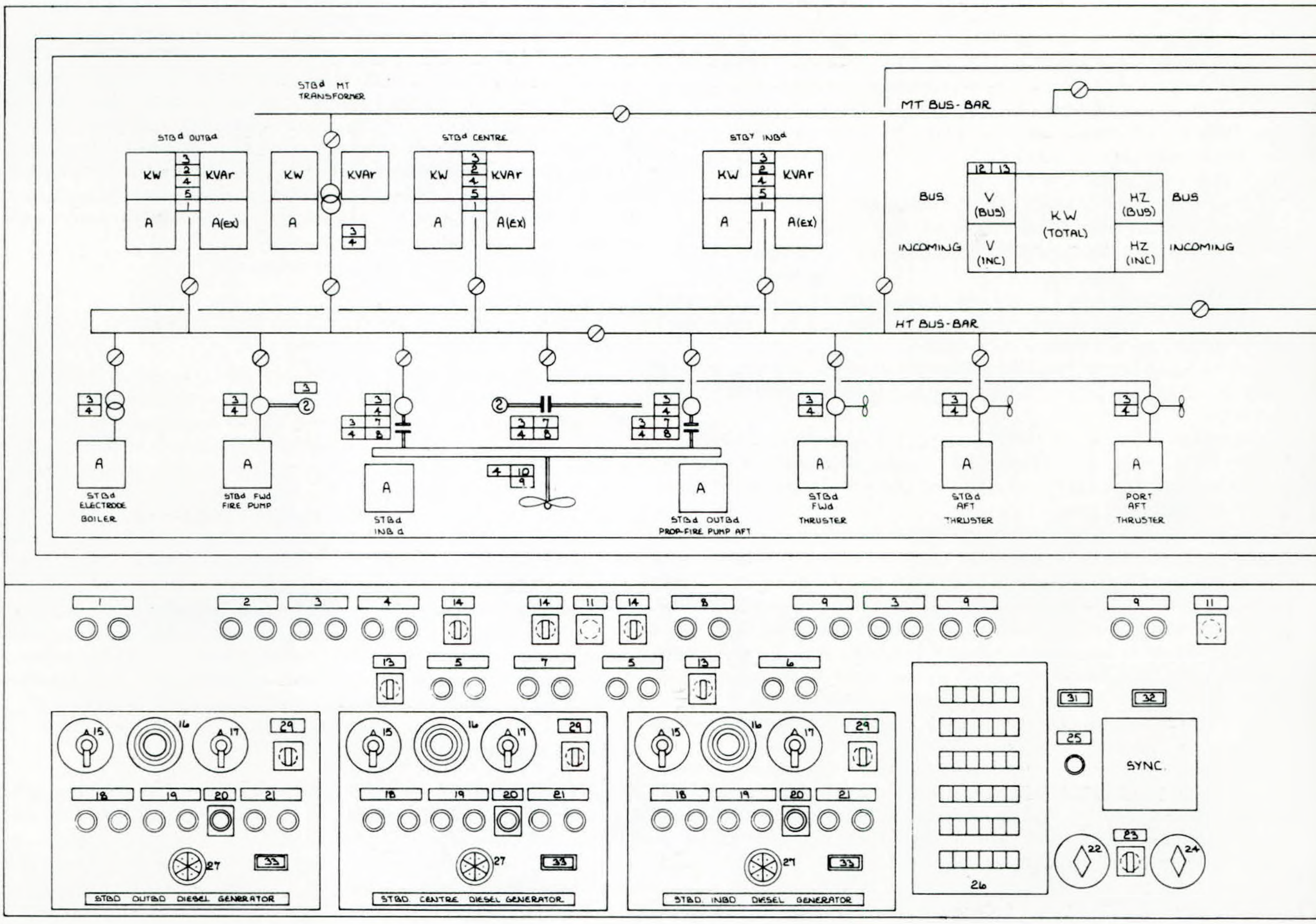
Selection of running and standby essential services is achieved from the MCR; however, these controls can be rapidly isolated at the starter, if desired.

Electrode boiler

An unusual feature of the vessel is its electrode boiler installation. This is integrated with a waste heat system[1] but may also operate independently.

The systems design of *Iolair* avoids incorporation of steam systems and, instead, maximizes the use of low-pressure hot water. A simple and effective means was needed, to supplement the main diesel engines' exhaust gas boilers.

After examining several alternatives it was considered that electrode boilers provided the best solution, for reasons including the following:



MIMIC INDICATORS		
No	ENGRAVING	COLOUR
1.	RUNNING	GREEN
2.	SHUTDOWN	RED
3.	FAULT	AMBER
4.	BLOCKED	AMBER
5.	STANDBY	BLUE
6.	SET AUTO	BLUE
7.	OPEN	RED
8.	CLOSED	GREEN
9.	BRAKE ON	RED
10.	BRAKE OFF	GREEN
11.	LOCAL MANUAL START	AMBER
12.	BUS VOLTS RED SCALE	WHITE
13.	BUS VOLTS BLACK SCALE	WHITE

DESK CONTROLS		
No	LABEL ENGRAVING	
1.	ELECTRODE BOILER CLOSE - TRIP	
2.	FIRE PUMP START - STOP	
3.	MAIN TRANSFORMER CLOSE - TRIP	
4.	PROPULSION MOTOR START - STOP	
5.	PROPULSION CLUTCH	
6.	SHAFT BRAKE ENGAGE - DISENGAGE	
7.	FIRE PUMP CLUTCH	
8.	FIRE PUMP/ PROP. MOTOR START - STOP	
9.	THRUSTER MOTOR START - STOP	
10.	TRANSFORMER CLOSE - TRIP TO STANDBY SW. BD.	
11.	BUS COUPLER TRIP	HINGED FLAP
12.	EMERGENCY GENERATOR START	
13.	MOTOR START INTERLOCK OVERRIDE	FLAP LOCK OFF
14.	EMERGENCY CLUTCH CLOSE OVERRIDE	FLAP LOCK OFF
15.	ENGINE SELECTOR OFF/ RESET - LOCAL MANUAL - REMOTE MANUAL - AUTO	KEY LOCKED
16.	A.V.R. TRIMMER	DIAL CLAMP
17.	ELECTRONIC GOVERNOR RAISE - LOWER	
18.	MANUAL START - STOP	

DESK CONTROLS		
No	LABEL ENGRAVING	
19.	CIRCUIT BREAKER CLOSE - TRIP	
20.	EMERGENCY STOP	HINGED FLAP
21	BALL HEAD GOVERNOR RAISE - LOWER	
22	BUS VOLTS SELECTOR SWITCH	
23	CHECK SYNCHRONISER OVERRIDE	FLAP LOCK OFF
24	SYNCHROSCOPE ON - OFF	
25	RESET PUSHBUTTON	
26	PUSHBUTTON SELECTOR	
27	SYNCHRONISING SOCKET	COVER FITTED
28	SYNCHRONISING PLUG STOWAGE	
29	GOVERNOR CHANGE-OVER SWITCH.	
DESK INDICATORS		
No	ENGRAVING	COLOUR
31	CHANGE SELECTION + RESET	AMBER
32	SYNCHRONISING PERMITTED	WHITE
33	BALL HEAD GOVERNOR MAX. RAISE POSITION	BLUE

- Generating capacity on the vessel is necessarily high, and the electrode boilers improve main engine load conditions at times when they would otherwise be running light.
- Thermal efficiency of these boilers is high and, even allowing for diesel generation and distribution losses, is as economic as oil-fired boilers for this particular installation.
- Control is simple and full modulation is possible between maximum and less than 10% full load.
- The units are robust, require minimal servicing, and are very compact for their output.
- Electrode boilers are extensively proven in shore-based service, both alone and in combination with waste heat systems.

Two 1 MW boilers are installed, fed via dedicated transformers from the 6.6 kV busbars. The boilers operate at 415 V and are protected against low flow, high temperature and high pressure.

After consultation with the makers, minor modifications were necessary to adapt the boilers for marine use.

Each consists of a vertical insulated cylindrical steel tank, with six hollow, tapered, cast-steel electrodes supported by insulators from the base. The top of the tank supports a small drive motor and emergency handwheel. A glanded bearing in the top plate supports a threaded drive shaft, from which is suspended a carrier plate mounting the borosilocate glass electrode shields.

The tank is filled with water and has inlet and outlet connections at bottom and top respectively. Two electrodes are connected to each phase of the supply. The tank is solidly bonded to the transformer star point and to earth.

A control panel including the main 415 V circuit breaker is mounted on the skid which also supports the boiler. In operation, the controls command the drive motor, raising or lowering the electrode shields.

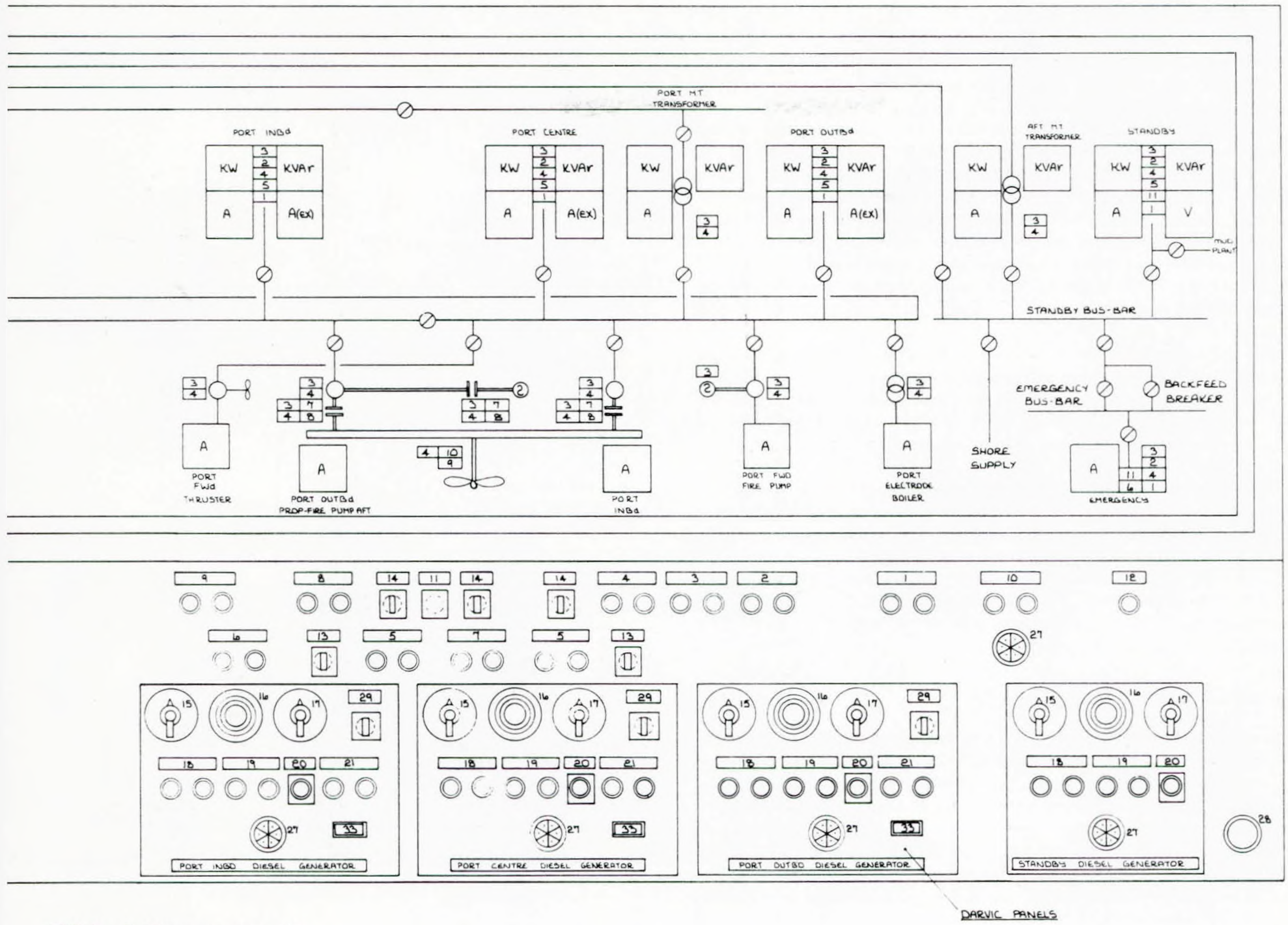


FIG 9 Setting-up console

The greater the area of the electrodes freely exposed to the water, the greater the heating effect.

The chemical dosage to inhibit corrosion in the low-pressure hot-water system was matched to provide an ideal level of salinity for operation of the boilers.

Small quantities of hydrogen and oxygen, generated at the electrodes, are vented up the funnel by means of pipes on the boiler top plates.

Lighting

High standards of illumination throughout *Iolair* were demanded, as illustrated by Table IV. Achieving these levels was difficult in certain instances, particularly for the deck and in machinery spaces in the pontoons and columns.

Each compartment, with the exception of minor stores, is served by at least two lighting circuits. One may be fed by the emergency lighting transformer since it is required to provide one-third of the lighting from emergency circuits. This ensures ample illumination for escape purposes, and for safe working to re-establish failed services. For safety, the berth lights are on the emergency supply in all cabins.

As a further back-up, on strategic routes and operating positions, a system of self-contained non-maintained temporary emergency lights is fitted. These units incorporate their own charger, sealed battery and inverter to give up to three hours of continuous illumination, initiated by loss of their mains supply. The arrangement reduces the cost and space for an alternative centralized battery and distribution system. Temporary emergency fittings have test buttons and an indicator light which turns off on low cell voltage.

Particular areas requiring special attention were dimmable floodlighting for the helicopter landing area (in addition to the landing lights themselves); and recessed moon pool lighting.

Additionally, the manual and remote-controlled very high-power searchlights were modified after consultation with the manufacturer, and provide illumination to standards pre-empting Lloyd's requirements for Firefighter Class II Vessels.[21]

OPERATIONAL FEATURES

System operating security

Iolair's operating roles impose different and varying load demands on the centralized power plant. Hence, the operation and security of supplies are major factors in design. Five automatic safety systems, as listed below, maintain the HT power demand and available supplies in balance.

1. Automatic call-up of generators to meet increasing loading demand.
2. DP computer limitation of total, and individual unit, loads.
3. Automatic limitation and reduction of pitch, independent of (2), acting directly on main propellor and thruster controls.
4. Preference tripping.
5. Independent safety systems for each unit of equipment.

The MT system has preference tripping and automatic call-up of standby and emergency generators dependent on the degree of power failure.

The MCR setting-up console (see Fig. 9) controls all six main diesel generators, main circuit breakers, the logic for automatic operation, load level at starting/stopping and load sharing.

In the automatic mode, the number of diesel generators running on duty and those on standby is programmed on a push-button matrix. Every combination of duty and standby set is catered for. The starting of a standby set can be due either to a fault on a running set or a signal from the load-level start circuit. The load-level start scheme ensures that loss of one running set does not cause the remaining sets to go into an overload of more than 10% (see Fig. 10).

Automatic limitation and reduction of pitch on the main propellors and thrusters is arranged to occur if an individual diesel-generator's sustained kilowatt load exceeds 110% full load.

Preference tripping of HT plant is arranged for both current and kilowatt loadings. Under fault conditions, the arrangement of plant may render the diesel generators either current-critical (for motors running lightly loaded) or kilowatt-critical with machines running at full load. Both preference tripping systems sequentially disconnect less essential items of plant until they finally trip one of each pair of the propulsion motors (Table V). Automatic limitation and reduction of pitch is incorporated in the kilowatt tripping circuit, preceded by the tripping of the fire pumps and followed by the tripping of the thruster motors.

The individual unit safety system is based on overcurrent causing pitch reduction on that unit, or tripping if permanent damage is likely.

Generators, propulsion and thruster motors are connected to the HT switchboard in such a way that the maximum security of the vessel's propulsion is retained in case of loss of any one section of the switchboard.

Cables from the high-voltage switchboard sections to the generators, propulsion motors and thruster motors are routed to minimize the effect of fire in any one space on the propulsive system.

Reliance on individual components was avoided by duplicating any that affected system security. Examples of this are in the setting-up console, where the load level start comparators and governor pulsing units each have duplicate circuitry with mode fault alarms and local indication for monitoring status.

Dynamic positioning

It is relevant to refer in this paper to dynamic positioning (DP), since it is a major part of any ESV's capabilities. In Ref. 22, DP is described as 'automatically maintaining the position and heading of a vessel within pre-defined limits by the exclusive means of self-powered vectored thrusts'. On *Iolair* this may be combined with mooring assistance, if required. The DP system encompasses all the elements required to achieve control of the vessel and not just the DP computer, software and reference systems as some engineers are accustomed to think.

The DP computers should be the most reliable part of the DP system, and the machinery systems were engineered to attempt to match this reliability. Power supplies for the computers and reference systems must be given equal consideration, have alternative sources and, in certain instances, be uninterruptible.

The philosophy is also extended to the feedback signals in such a way that pitch, power and absorbed current are correlated. This enables the computers to identify not only a fault condition, but also to determine whether the fault is in the control or the feedback. This is an important asset on such a vessel where the implications of unnecessary disconnection of a major thrust contributor may be far reaching.

The constraints placed on the designers of the computer hardware and software caused some misgivings, since they did not permit use of the manufacturers' standard techniques throughout. However, we believe that the DP system performance will be improved as a result of the multi-disciplinary approach applied.

Operational, maintenance and fault-finding aids

Early consideration was given to operational, maintenance and fault-finding aids. Operators must be able to assess rapidly system status, and extensive use of mimics has been adopted for purposes as diverse as mooring control and power system setting-up. This enables personnel to recognize rapidly the implications of their action and institute corrective procedures if faults occur.

An extension of this philosophy is the provision, in some control panels, of light-emitting diode displays to aid fault finding in interlock circuits and to permit rapid location of faulty modules or components.

Condition-monitoring techniques are employed for all rotating plant. Shock pulse adaptors are fitted to all motors, size permitting.

The 6.6 kV; 415 V and 240 V systems are provided with earth leakage monitoring equipment so that any deterioration in insulation level can be detected, with alarm facilities for exceptionally low levels. In addition, the 415 V systems are fitted with earth-fault location equipment using a fixed, low-frequency injection unit with a portable tuned clip-on toroidal transformer and meter. This obviates the nuisance generally associated with insulated systems for isolating each circuit in turn to locate the fault.

Table IV: Minimum illumination levels

AREA	ILLUMINATION LEVEL (lux)	
Accommodation		
Cabins	200	
Offices	500	
Toilets and shavers	200	
Passageways	100	
Stairways	150	
Mess and public rooms	300	
Hospital treatment areas	500	
Navigation areas		
Chart table	750	
Control bridge	200	Thyristor controlled
Stern observation position	200	Thyristor controlled
Computer room	200	Thyristor controlled
Radio room	500	
Operating areas		
Galley	500	
Commissary and laundry	300	
Access and casing	100	
Machinery spaces	250	
Machinery control room	150	Fixed, up to 400 thyristor controlled
Switchboard room	600	
Steering gear	200	
Motor rooms	200	
Pump rooms	200	
Workshop (M/S)	400	
Workshop (deck)	500	
Stores	200	
Deck	50	Working areas, 25 elsewhere
Helicopter landing area	50	
Gangways	100	
Overside (sea level at operating draught)	100	

Notes:
1. Areas for which illumination levels are not given are illuminated to the level of an area serving a similar function.
2. The new condition levels are achieved by multiplying the above levels by a factor of 1.2.
3. All values are for horizontal illumination.

Table V: Sequence of HT preference tripping for kilowatt or current overloads

KILOWATT	CURRENT
1. Trip fire pumps	1. Trip MT non-essential loads Trip fire pumps Trip electrode boilers
2. Pitch reduction on thrusters and propulsion units	2. Trip thrusters
	3. Trip one of each pair of propulsion motors

Extensive cable routeing drawings are supplied by the shipyard's electrical contractor to enable any cable to be followed throughout its length. All cables, cores, internal wiring and terminals are identified, as are individual components within the panels. This approach is intended to speed recognition of circuits when fault-finding; thus easing the high daily routine workload of the vessels' three electrical officers.

Further localized aids to ship's staff are test plugs, incorporated on each of the grouped starter section boards, with power sockets and internal lighting for each console and local control centre. Comprehensive test facilities are provided in two workshops for electrical and control equipment.

Iolair is designed with permanent welding current distribution in all machinery spaces.

Permit to work

A formal procedure is required for safe working on the HT system because of:

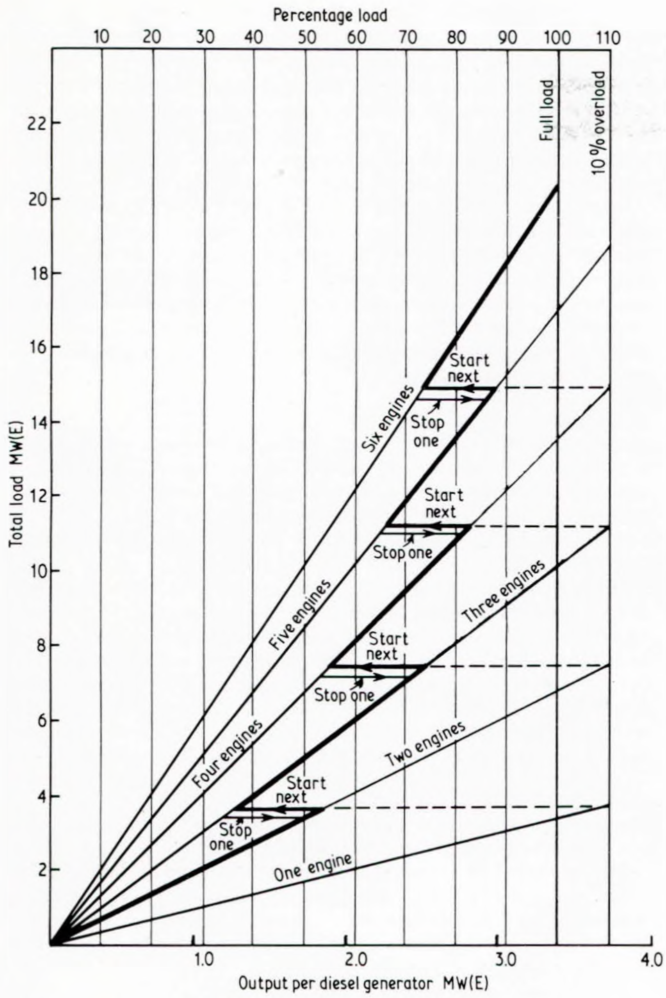


FIG 10 Engine start-up levels

The danger existing from high voltage.
The level of automation.
Changes in personnel on watch, and onboard, during repairs.

The permit to work system that exists in the electrical supply industry was adopted as a basis for the system on *Iolair*. The basic procedures can be categorized into three sections:

1. Isolate, lock off, apply caution and safety notices.
2. Test and apply earths to ensure a safe working zone.
3. Retain the means of re-energizing the system in a safe place, until it can be recorded that all work has been completed and the working team are clear of the job.

To comply with the three categories above, safety keys are used. Only one key exists for each dedicated padlock; these padlocks are to be applied at every position where it is possible to re-energize the part of the network which is to be worked on (e.g. engine fuel racks and voltage transformers; as well as connecting circuit breakers).

Integral earthing is provided on the high-voltage switchboard via selector switches and, once the circuit breakers are closed in this position, they can only be tripped manually at the local position.

The method of recording that the system is safe to work on involves a form detailing in writing with the aid of a diagram the points of isolation, application of padlocks and earths. This form may only be issued by an authorized person who, in addition, is responsible for safeguarding the padlock keys until the work is signed off as completed.

CONCLUDING REMARKS

No single paper of this nature can deal comprehensively with the electrical systems of a vessel such as *Iolair*. The novel construction demanded a re-examination of traditional concepts, for which there is seldom opportunity in conventional ship designs. We believe that, as a result, *Iolair* is uniquely equipped to perform her functions with a level of safety which will be appreciated by the ship's staff, offshore personnel and operators alike.

The philosophy of the *Iolair* design necessitated a change in approach to the ship construction and outfitting which was embodied in the builder's initial proposals. An extensive and complex specification demanded the utmost effort from shipbuilders and subcontractors alike, in adjusting their normal procedures to meet these exacting requirements. While this should be a caution to both designers and builders involved in similar projects, it is to the credit of construction teams that they eventually achieved all their principal objectives.

ACKNOWLEDGEMENTS

The authors wish to thank the Directors of British Petroleum Company p.l.c. for permission to publish this paper; and their colleagues both within and outside BP Shipping Limited for their assistance and advice.

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Discussion

B. FOWLER (J. Charters (Marine) Limited): I thank Mr Rush and Mr Taylor for a paper which has meant a great deal of effort on the part of both. Obviously it would be foolish to deny that this contract did not strain relationships at times but I am happy to report that our relationships, and also those of the overall technical team, have emerged intact.

At the outset it was apparent that Charters would have to reorganize to do this special job. Following discussions with BP and Scott Lithgow, the main contractor, it was decided to alter the structure of the company to provide the services such a complex vessel demanded. These were, quite simply, technical, planning and quality assurance. The design function was supplemented by qualified technical assistance and an Assistant Chief Draughtsman was appointed to control detail drafting and increased staff.

Right at the outset, the principles of quality assurance were laid down, followed by a plan to create all the necessary documentation. Standard-practice data sheets which reflected current operation, test procedures for electrical equipment and a quality assurance manual outlining responsibility and procedure were all written and submitted for approval. Perhaps the data sheets were the most important as they ensured common practice throughout the ship and avoided the difficulty of electricians' indulging their personal training.

Planning was set up using experienced foremen and electricians. Since the expertise did not exist within Charters, a consultant was employed to train staff in network analysis, monitoring and forecasting, including all aspects of project control. The real success of this measure was in the ability to know, from week to week, not only where you had been but also where we were going. Ratios of estimated hours to actual hours were carefully scrutinized each week, as these reflected the relative productivity being achieved on each cost centre in the vessel, and were a valuable source of data for use in future contracts. Initially, we had some misgivings about project control, seeing it only as an additional overhead; but, after a year, it became clear that we could not have controlled our costs or maintained our target dates without it.

The technical aspects were of course vital in the early stages, as any mistake in specification could have proved extremely costly.

HT Cable

As stated in the paper, BP were persuaded to allow us to add a CSP sheath over the HT cable braiding. This was mainly because of the pulling-in problem: for instance, the aft propulsion motor runs are some 130 m long, installed in one continuous length, and were routed from the HT switchboard through the engine rooms into the column tops down the legs and along the pontoon tunnels, involving some 12–20 changes in direction. Obviously, careful planning of the route was required, each 'pull' requiring the efforts of approximately 40 men. Fortunately, there was very little damage to the sheath, only three or four repairs being required.

Before deciding on EPR–CSP HT cable, considerable thought was given to other types of cable. It is recognized that cable having a semiconducting layer over the insulation could have been used, being marginally cheaper. However, we finally came to the conclusion that EPR–CSP was preferable because of:

(a) Easy termination without the use of special cable-jointing skills, eliminating the need for stress cones.

(b) If repair is required when the ship is in service, this can be carried out by ship's personnel without the need for skilled jointers.

(c) The thickness of insulation used gives an impulse level of about 200 kV.

When the HT cable network was finished, pressure testing—bearing in mind the responsibilities of the Health and Safety Act—was carefully planned. On three consecutive Saturdays (which were wet even compared to Greenock's standards), the boat was sealed off with a special security guard and only people with special passes were allowed aboard. A 24 kV dc was applied to each phase core for five minutes and all the other cores were shorted together and earthed.

MT and control cables

These are of conventional type, the main problem being their weight—200+ tonnes. A great deal of thought was given by the drawing office to routeing, cooling and recording of routes. Segregation of intrinsically safe runs was particularly difficult.

The amount of welding for ducts, and the number of brackets required, called for a great deal of co-operation from yard management.

415 V Motors and control gear

A major co-ordination problem was in ensuring that motors for all auxiliary equipment and associated control gear met BP's stringent requirements. With the co-operation of the local GEC office, a monitoring system was set up whereby subcontractors' orders for motors were notified to us and then to GEC so that requirements were met.

Motors are all CMR rating and, as a philosophy, engineers were asked to design to 90% of the CMR rating; therefore, with thermal overload settings at 90% of FLC, tripping occurs at 108% full-load current in approximately two hours. It is surprising that many mechanical design engineers did not realize that CMR means what it says—the continuous maximum rating of the motor. There is little allowance above this figure for overload operation, therefore protection should be co-ordinated accordingly.

Switchgear

The co-ordination of delivery and testing of switchgear and control gear was a major task in itself. Delivery had to be co-ordinated so that construction of the vessel was not delayed. This resulted in very tight delivery schedules and, in some cases, manufacturers did remarkably well in reducing their quoted delivery times to meet the deadlines. Particular credit is due to LS&E in this respect.

The HT switchgear was a case in point, where the works test schedule indicates the amount of work required at this stage. These tests, with the co-operation of BP, GEC and Lloyd's Register, were carried out in 7 days, night and day. The amount of testing on the HT switchboard, after erection on board, is again illustrated by the thickness of the appropriate test form. A great deal of time was probably saved by preparation of these documents so that both test engineers and witnessing authorities knew exactly what was to happen.

Jeopardous activities

The special jeopardous role, mentioned in the paper, required isolation of a wide range of services that could constitute a major risk if permitted to operate in the presence of gas. Almost 130 services have to be shut down in two stages under these conditions. A fair proportion of these services are vent fans, which also require remote shutdown for fire and CO_2 flooding, to meet DOTI requirements. The total DOTI shutdowns covered 180 auxiliaries.

To cut down on the cabling network for these trips, 32 relay enclosures were sited at strategic positions around the vessel, mainly at the rear of motor control centres. The local stops from each starter were taken to these enclosures with multi-core cables to the bridge; as an added protection against fire, all remote stop/shutdown cables were insulated with silicone rubber or glass mica.

Switchboard instrumentation

A particularly difficult aspect of the installation was the switchboard instrumentation. Instrument accuracies vary between 1 and 1.5% of full-scale deflection; when it is realized that the generator trials involved the reading of some 83 instruments, it was obviously a very difficult problem which tried the patience of our own engineers, BP superintendents and Lloyd's Register.

An addition which we made to the switchgear specification was to add, on convenient switchgear panels, GEC test blocks into which standard meters could be easily connected. This, coupled with a fast reliable calibration service, which is available locally, enabled most of the problems to be resolved.

Generator testing

For dockside testing, we originally envisaged the use of two salt-water tanks of some 11 000 l capacity which were capable of absorbing 4 MW. These, coupled with four-off 600 kVAR continuously-rated reactors, allowed full-load testing of each machine at rated power factor and, obviously, half-load testing of two machines in parallel. It was anticipated that, with accurate setting of recording of governor droops with this amount of load, it was reasonably certain that full-load testing would be a matter of course.

It eventually transpired that we were able to load three machines up to full load in parallel by using the above equipment and by being allowed to use the electrode boilers. It was possible to run machines for full-load tests for 12 hours using the above equipment, it being necessary to introduce air pipes which were fitted to the bottom of the tank and perforated to allow an even flow of air through the salt water solution. The load was applied through two-off 6.6 kV/415 V transformers.

Aluminium test cables were used to connect between each of the test tanks, coupled with two reactors, to separate sections of the main MT switchboard busbars. Six single-core 350 mm^2 cables were used for each phase connection.

Push-button control of the test tank and reactors was arranged from the HV switchroom.

Conclusion

It would not be appropriate for me to finish without recognizing the willing help of those who have become colleagues in the every sense of the word, i.e. the experts from, particularly, LS&E, GEC Switchgear, Whipp & Bourne, A. Watson & Dundas, Pirelli Cables and Strathclyde University, who spent many long hours at meetings seeking solutions to the problems which arose.

Next month, *Iolair* will sail—a floating power station of wholly British design and construction and I am sure we shall be proud of her.

G. P. ROYLE (Electrical Manager, Scott Lithgow Limited): In their introduction, the authors state: 'The introduction of features completely foreign to existing practices could have invited extended delivery periods and prohibitive costs'. I should like to point out that new concepts in marine electrical engineering have been incorporated by the shipbuilder without extending delivery, e.g. DP computers in drill ships; and at a reduction in cost, e.g. multiplexed container-monitoring in cargo vessels.

With regard to short-circuit calculations, it should be noted that Scott Lithgow have traditionally had these calculations carried out in depth on previous contracts, using IEC 363 backed up, on vessels with electrical propulsion, by simulation studies carried out by the main supplier of the electrical generation and switchboard equipment.

I do not think the sentence at the top of page 8 reads correctly. In fact, the traditional use of the 2.55 multiplication factor to allow for ac and dc components at low power factor gives an excessive estimate of the fault-making level and could result in the use of circuit breakers with greater fault capacity than necessary.

In view of the emphasis on safety in the design and operation of *Iolair*, I should like the authors' comments on two points:

(a) Would it not be 'safer' to run with interconnectors closed rather than open? This would mean the whole system would be continually synchronized, 6.6 kV and 440 V, and therefore there would be no delay, however slight, whilst supplies are changed from one set of busbars to the other.

It would appear that the system's protection is such that any fault could be cleared with minimum prejudice to supplies and safety, if full zone-differential protection was provided.

(b) Whilst noting that the diving switchboard is unique in so far as it has direct feeds from main and standby switchboards in addition to a feed from the emergency switchboard, would it not be more logical and safer to have two separate diving switchboards?

In addition, would the authors like to comment on the following points:

(i) Was thought given to the use of synchronous induction motors to give improved power factor at low loads?

(ii) With regard to the selection of HT transformers, nitrogen has a poor heat transfer characteristic. Was this the reason for fitting fans after works tests? Would the cast-resin type now be considered?

(iii) The use of trolleys for synchronizing across the busbars is accepted practice on land. What provision is made for securing the trolleys against vessel motion?

T. D. MEYLER (GEC Electrical Projects Limited): Although the system's neutral is not connected to earth, the system is earthed through its own capacitance and the authors indicate that the capacitive current into an earth fault could be over 4.9 A, which is unpleasantly close to the 5 A taken as the lower limit for arcing grounds. However, the figure of 5 A, though often quoted, is likely to have some tolerance in one direction or the other.

It is stated that resistance earthing is critical with respect to resistance value, but this is true only with respect to the optimum value, i.e. $R = X_c$. This value gives adequate damping and minimum fault current, but lower resistances can be used and so only the maximum value is critical.

No mention is made of the type of fault discussed by Dunki-Jacobs. This is a 'high-resistance' fault to earth in a winding. His tests showed that 3 A fault currents caused a cycle of intense local heating followed by a cooling-off period, when the fault resistance became low and the dissipated power fell, and this cycle continued until the test was stopped. The burning and smoke would not be acceptable for long and the faulty machine would have to be taken out of service. But the philosophy of the ESV design is rightly based on accepting that any single item of plant may have to be taken out of service without warning, because of an electrical line or mechanical fault, so no new concept would be introduced if earth faults also caused a trip. The effect on machine MTBF should be marginal; and the system MTBF should be improved since the adverse effect of running with one line earthed is avoided.

If earth faults are to trip, they must produce a fault current sufficient to obtain automatic location of the fault, including faults well down from the line-terminals of machines (delta windings can be completely protected).

A value of 10 A is adequate and is only about double the maximum capacitive value expected. The exact current can be selected to damp arcing grounds in systems of high capacitance, such as those in which capacitors are connected at machine terminals to absorb steep-fronted wave fronts: this is recommended by Cornick and Thompson for systems with vacuum breakers, to reduce the inter-turn stress in line end coils.

One objection to earthing resistors is that they are usually connected to generator neutrals and this results in high earth-fault currents when all generators are connected, unless a switching arrangement is provided. This can be avoided by using small interconnected-star earthing transformers with the resistor connected between neutral and earth. One assembly per bus-section is required, supplied from a fused vacuum contactor, and only one is used per interconnected busbar, i.e. normally only one is in service. The transformers are quite small, weighing about 150 kg.

Core balance transformers and sensitive relays can detect fault currents of no more than 2 A, and a back-up CT in the earth connection will detect busbar earth faults which, although unlikely, have such serious consequences that early detection and location are desirable. Stability can be assured by introducing a short time delay; and, if essential, the delay could be extended to about 30 s to enable standby plant to be connected before tripping the faulty unit.

This system is used in industrial systems and is being applied in marine applications. Its advantages are:

1. The fault current is not greatly increased over the capacitance value in a large system.
2. It will suppress arcing grounds even if system capacitance is artificially high, as when surge-suppression capacitors are installed.
3. It will detect high-resistance faults, which can produce extensive burning and smoke emission, without significantly increasing the fault damage at a low-resistance fault.
3. It provides a means of locating faults so that appropriate action can be taken without having to disconnect successive circuits.
5. Equipment used is standard and does not take up much room.

Under the heading 'Dynamic positioning', it is stated that the DP computer should be the most reliable part of the system, yet the power management system is not microprocessor-based but uses relay circuits. Would a design study starting today change this apparent anomaly?

Bibliography

(a) J. R. Dunki-Jacobs, 'The Reality of High Resistance Grounding'. *IEEE Transactions Industry Applications,* Vol. 1A–13 No. 5, pp. 469–475 (Sept./Oct. 1977).

(b) K. J. Cornick and T. R. Thompson, 'Steep-fronted switching voltage transients and their distribution in motor windings', Parts 1 and 2. *IEE Power Applications,* Vol. 129 Pt B No. 2, pp. 45–63 (March 1982).

(c) C. B. Cooper, 'Neutral earthing for ships'. *IEE Conference on Earthing,* pp. 28–32 (March 1972).

R. L. AMES (Laurence, Scott & Electromotors Limited): I feel that the authors have somewhat abbreviated the data given for the machine insulation parameters, in that the details of the interturn voltage design and test withstand values have been omitted.

The sentence should read: '*Iolair*'s machinery is designed to withstand surge levels to earth of 31 kV peak and, between turns, of 8 kV peak. These levels are maintained for at least 20 000 switching operations, which is the design life of the insulation under current chopping and multiple pre-strike phenomena respectively'.

M. J. BOLTON (YARD Limited): The authors have shown a preference for an insulated neutral high-voltage system and, whilst I find myself generally in agreement with their conclusion, I am less in accord with the supporting arguments. They do seem to have taken a somewhat simplistic view of resistance earthing, considering only the case where the resistive component of the fault current is equal to the capacitive charging current. Although this approach gives a minimal earth fault current while ensuring that large transient overvoltages cannot build up on low-loss systems such as HV transmission lines, it is not appropriate to higher-loss marine distribution systems where, in any case, the resistance is normally chosen to give an adequate earth fault current for reliable automatic isolation.

Of resonance earthing, the authors say that, if one phase has an earth fault, the voltage on healthy phases rises to three times the normal voltage but is this really very different from what would happen on an unearthed neutral HV system? I am not aware of any faults which have resulted from this cause so far. Would the authors care to comment further?

Of resistance earthing generally, the authors refer to the disadvantage of large resistors with consequent heat dissipation. But, with high-resistance earthing, the size of the resistors is small and, even with low-resistance earthing, they are rarely so big as to cause a problem, as they can be totally enclosed and put in a convenient location away from the areas where space is important. Earthing resistors are, of course, short-time rated and heat dissipation should not be a problem in a well-designed system.

The authors' solution to busbar protection is interesting. In many marine installations, operators traditionally have preferred to keep protection as simple as possible, partly because of the sometimes doubtful performance of protective gear at sea, and they have tended to assume busbars as a fault-free zone. In *Iolair*, the need for power-supply integrity is paramount and most would agree that properly designed busbar protection should be applied. In an installation of this nature, it is important to limit fault damage to a minimum; hence my inclination would have been to go for some form of split-bus differential protection with its simplicity, fast operating time and avoidance of the need for time discrimination. Could the authors comment on this in relation to their choice of directional protection for this system?

The paper also includes overvoltage protection in Table III and I should be interested to hear of what this consists. In a high-integrity system of this nature, one would hope to see a potential overvoltage, caused by, say, AVR failure, suppressed at source and the faulty excitation equipment automatically replaced by standby gear. I speak with some feeling about this, as, in a 3.3 kV installation, I once experienced an overvoltage exceeding 5 kV which seriously damaged essential services. In that case, we fitted protection which caught a potential overvoltage on its way up and tripped the excitation to a pre-set manual setting, thereby avoiding the need to shut down the generator.

S. SARKAR (Whipp & Bourne (1975) Limited): The authors are to be commended for the preparation of such a comprehensive paper dealing with the various aspects of the electrical system for an emergency and support vessel.

The differential protection used for the protection of the generator and motor is of bias type. In an installation of this type, in my opinion, an instantaneous (high-impedance) type of differential protection is advisable, as this will provide much faster operation and, hence, less damage. Possibly the authors would wish to justify the choice of bias-type relays.

Figure 4 shows that the DMT of the generator short-circuit protection is 3 seconds. This is considered to be too long and a figure of 1 second or so is desirable from the point of view of damage, say, to busbars. From Fig. 4 it would appear that the DMT could be reduced to 1 or 1.5 seconds.

Perhaps the authors would clarify the significance of the bands shown on the bus-section short-circuit curves. It is not clear whether these two curves are expected to discriminate between each other. If so, under certain operating conditions the time-grading margin does not appear to be adequate.

Would the authors clarify whether the motor-protection relay selected will provide adequate protection against locked-rotor (cold and hot) condition?

Are the capacitances of the plant and cable, quoted in Table I, estimated or measured values? If estimated, do the authors intend to measure the values? Generally, the estimated values are pessimistic and it would give additional peace of mind to the authors that overvoltage is not likely to occur if the measured value of capacitance is found to be appreciably lower. The value of transformer capacitance is not given in Table I. Is this because the data are not available or is the value negligible?

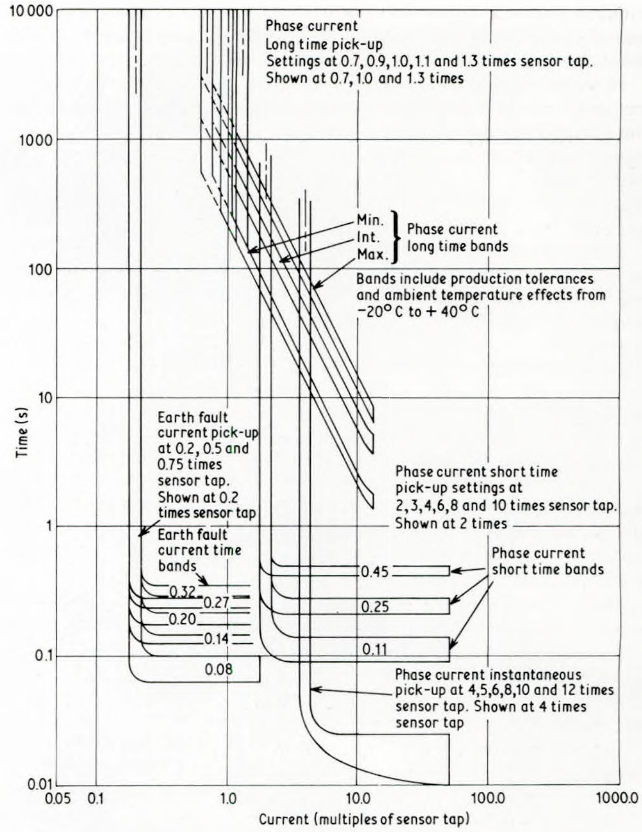


FIG. D1 Static overcurrent trip device: time–current curve

The authors have selected an unearthed system but is it not the case that the earth leakage monitoring equipment used will allow a certain amount of earth fault current to flow?

While the authors have mentioned that full-co-ordination of protection on the entire system is achieved, I should like to take this opportunity to add that this has only been possible with the use of a solid-state protection device on the 415 V system. This relay has been designed to match the characteristic of the moulded-case circuit breaker and the fuses. The relay has long-time and short-time characteristics, as shown on Fig. D1. With this type of protective device, it has been possible to trip the standby generator in 0.45 seconds and the 2250 kVA transformer in 0.75 seconds without sacrificing selective protection.

D. GRAY FIMarE: I think this is a splendid paper. It illustrates how the operational requirements determine the main parameters of the electrical system and how the latter then dictate the specification(s) for the individual items of equipment. I am sure it will be studied by many engineers in the future. My warmest congratulations to the authors.

In the section 'Propulsion machinery considerations', there is a reference to transient voltage dip being less than 15%; also, Fig. 5 demonstrates the satisfactory transient performance of propulsion-motor starting. However, presumably in order to obtain satisfactory system performance, the transient performance of individual generating sets must have been defined in the specification. Could the authors give the transient performance demanded of individual generating sets, for both frequency and voltage, in terms of base load, load change, maximum permitted deviation of frequency (or voltage) and time permitted for frequency (or voltage) to recover, for both kW loads and kVA loads respectively?

It could well be that the presence of the DP computer was the major factor in dictating the tightness (or otherwise) of voltage and frequency transient response. It is well known that some computers have been, and are, rather sensitive regarding stability of power supply. Could the authors shed some light on this?

Since the DP computer is dealing with real-time problems then no doubt digital techniques are being employed. Could the authors indicate whether, for control equipment generally, digital techniques, multiplexing and optical fibres were used or considered for use? The use of multiplexing and optical fibres would seem to be appropriate, since the authors have referred to space problems.

Have there been any problems with the computer regarding electromagnetic interference? There have been instances where such interference has prevented the processor carrying out the program; there have been cases where the program itself has become contaminated. The system has not always been restored to the operational state by restarting the computer; on occasions it has been necessary to read in the program from tape. This operation can be far from simple.

Short-circuit currents have been mentioned in the paper. Could the authors say whether short-circuit tests were carried out on the generating sets, i.e. both prime mover and generator, as a type test? I am aware that such a type test is rare in commercial shipping circles, but it was always demanded as a type test for generating sets ordered by the Navy and probably still is a requirement. The advantages of proving the ability of the complete generating set to withstand short circuit before the equipment goes on board do not need to be spelt out. It would seem to be of particular importance in this ship, in view of the security demanded of the electrical installation.

A. C. BAILEY (Lloyd's Register of Shipping): This paper reviews design options that were available in respect of system voltage and earthing, protection, power management and system interconnection. It makes clear the reasons for decisions that were taken and shows that much care and thought have gone into the design of the electrical system—in fact, a thoroughly professional job.

Some years ago this paper might have caused eyebrows to be raised; some years hence, it could be regarded as old hat. At this time, however, it is of great interest because it describes a new and complex HV system, rare in marine circles.

Clearly, ventilation is relied upon to a large extent. It would be interesting to learn whether operational situations are anticipated in which a supply of clean air would be doubtful or impossible.

Again, it would be interesting to learn what led to the choice of electrical equipment in the potentially hazardous areas. Was this choice primarily governed by practices pertaining to conventional tankers; or guided by offshore concepts involving area classification?

R. G. BODDIE FIMarE: Thirty years ago, there were problems in finding the capacity in the UK to produce the production drawings for the large aircraft carrier which was never built. Could the authors please say if *Iolair*'s machinery was designed as a system or as separate units; who co-ordinated the system design and with what success, and what changes, if any, they would recommend with hindsight for this type of large and complex design?

Authors' Reply

We are indebted to Mr Fowler for his remarks and for the wealth of practical detail which he has given. We hope that his comments will be recognized for their value in assisting those undertaking future projects to prevent, or surmount, the sort of difficulties which may otherwise arise.

Regarding the contribution by Mr Royle, it must be remembered that, at the time of writing the specification, we did not know with which shipbuilder the final contract would be placed. Not all shipbuilders possess the skills, capacity and experience necessary to handle a novel concept of this type. Also, it is our experience that shipbuilders do not always perform their short-circuit calculations in the manner which Mr Royle claims for his company.

In the matter of circuit-breaker ratings, we believe we are of one mind, but have chosen different words in its expression.

Interconnectors on the 6.6 kV system are normally closed, forming a common bus although not a closed ring. Prospective fault levels on the 440-V system precluded a similar operation which, in practice, has not proved in any way detrimental.

Two separate diving switchboards would have required a much more complicated arrangement with, possibly, less flexibility. As every cubicle is fully segregated, with facilities to disconnect from the bus, we believe that the arrangement is amply secure.

Synchronous induction motors were considered but, in certain conditions (for example, fault or loss of one propulsion motor), they do not have adequate torque. In addition, they would have been much more costly and do not have the simple robustness of a squirrel-cage induction motor. As we have demonstrated, we do not have a problem with the power factor.

The reason for fitting fans to the transformers, after the works test, was a mistake in dimensioning of the original tanks. These proved too small, thus impeding nitrogen circulation. Gas having superior heat-transfer characteristics was tried; but, again, this was unable to circulate. Fitting external fans may seem an odd way to improve internal circulation, but it worked!

Cast-resin transformers would now be considered.

The bottom of the HV switchboard is provided with small brackets, into which support bars on the synchronizing trolleys latch.

Mr Meyler and several other contributors have commented on aspects of our selection of the unearthed neutral system. Without a mention of this topic, we felt that our paper would be incomplete for those marine engineers less familiar with other alternatives. It was not intended that this mention should be regarded as a detailed treatise. The subject is guaranteed to provoke comment from electrical engineers and all those made are entirely relevant. However, having weighed all these factors and many others besides, we concluded that, for this vessel, the unearthed system as designed would be safe and simple and would provide an ability to continue operating with redundancy even if a single earth fault developed.

Depending on the operation in progress at the time a fault developed, this increases the options available to the operators, at least for a limited period.

With regard to the power management system, a microprocessor-based system would certainly be considered in a design study commencing today. We do not, however, believe it to be an anomaly that such a system was not used previously. It is by no means certain that it would prove either the best or most cost-effective solution now, given the same design criteria.

Mr Ames has rightly drawn attention to an omission in the data given for the machine-insulation parameters and we are grateful for his correction.

Mr Bolton refers to the increased stress between the phase conductor and earth (ship's hull) of a resonance-earthed system (although he incorrectly quotes $\sqrt{3}$ as 3 times) and, quite rightly, states that this is also the case for an unearthed neutral system. However, the comparison between the two systems is based on the capacitive values varying (as is the case when circuits are connected and disconnected due to normal operating requirements), which affects the tuning of the coil. As the word 'resonance' states, it is based on limiting fault current due to a balance in circuit parameters (inductance, resistance and capacitance) and, for a small system such as that on *Iolair*, with the problems of ensuring tuning, we consider the use of a resonance earthed system has more disadvantages than advantages.

We believe that the size and cooling requirements of the resistors of a low-resistance earthing system are underestimated by Mr Bolton; and in fact all space and weight on *Iolair* were very much at a premium.

The choice of busbar protection was based on a number of factors which precluded the use of a differential scheme. It is assumed that the reference by Mr Bolton to split-bus differential protection is a scheme using high-impedance relays with their inherent fast operating characteristics. This scheme requires the fitting and then interconnection of current transformers in the circuit breakers of all generating plant, consumers and bus-section circuits themselves. This introduces common mode failure conditions of interconnecting wiring between all the circuit breakers in the zone, which the design philosophy avoided wherever possible. It also meant that the number of current transformers in individual circuit-breaker cubicles would be increased and there was a space constraint imposed by most manufacturers' equipment.

To overcome the common mode failure of interconnection of the differential protection scheme, it would be necessary to ensure that duplicate measurements were performed and that the malfunction of the single tripping relay, as is normal on a system of this type, could not cause, by a single action, the loss of a complete bus-bar section.

Additionally, the condition of a fault on the bus-section circuit breaker itself has to be covered. This is normally done by introducing a delay in the tripping of the consumers and generating-plant circuit breakers on that section. For these reasons, the simpler and more secure directional system was adopted.

The over-voltage protection referred to in Table III is not of the suppression type, as described by Mr Bolton, but does in fact isolate the source of the over-voltage. The automatic correction of an over-voltage by replacement of the AVR with a standby unit is an interesting concept and, with a fully engineered design, is seen as having a number of advantages. It is worth mentioning that the insulation levels of modern equipment would not suffer from the over-voltage suggested by Mr Bolton but there is room for improvement in future designs by exploring this idea.

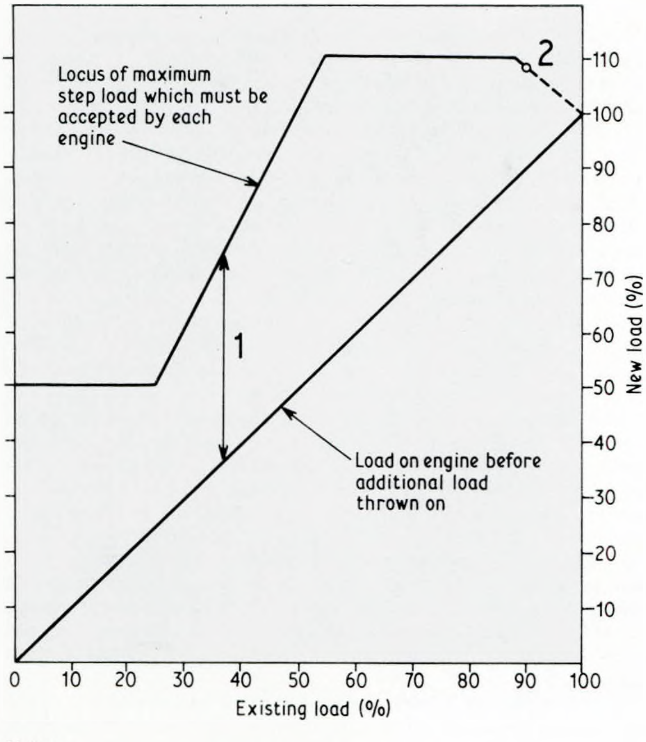
Mr Sarkar asks what the justification is for using biased differential protection in preference to an instantaneous differential protection system of the high-impedance type. It is appreciated that this protection offers faster operation but our selection was based on the operation of this unearthed network with an earth fault present for a period of 24 hours. This being the case, the effect of 'spill currents' on the operation of a differential-type protection scheme could have been undesirable and the biased option was chosen to eliminate this.

The time delay chosen for the operation of the generator short-circuit protection is not entirely due to the curves shown on Fig. 4. Missing from this diagram is the reflected current due to a short circuit on the secondary side of the main transformers and its protection clearance time, which necessitates the delay of the generator protection. We would agree with Mr Sarkar that it is desirable to clear a bus-bar fault as quickly as possible but would add that the bus-bars have a 3 second rating, which is adequate for these settings.

The bands shown on the bus-section short-circuit curves are relay tolerances and testing confirmed that no problem existed due to discrimination.

The motor protection, although not incorporating specific locked-rotor protection, does provide adequately for the locked-rotor fault condition.

The values of capacitance quoted in Table I are in fact values as measured in the machine manufacturer's works and cable manufacturer's works (for a 1000 m run). These cable values are then calculated, as accurately as possible, for the length installed on the vessel.



Notes

1. Magnitude of step load which must be accepted, giving:
   Momentary variation = 10% maximum.
   Permanent variation = 4% maximum.
   Recovery time to 1% steady load speed band = 3 seconds maximum.
2. When operating at design maximum load, on six engines, this instantaneous load acceptance must be achieved at 90% load in order to avoid a blackout if one engine trips.

FIG. D2 Required load acceptance capability of main diesel generators

The transformers have a capacitance, according to the manufacturers, which can be regarded as negligible. In the limit, we would agree with Mr Sarkar that the value of capacitance for the overall system should be confirmed by measurement. This, however, is not easy to achieve and since, for this vessel, sufficient confidence existed in the calculated values, such testing was not performed.

In reply to Mr Sarkar's last point regarding the use of earth leakage monitoring equipment, this does allow a current to flow to earth but this is restricted to within 30 mA for a zero impedance earth fault, as required by IEC for circuits passing through potentially hazardous areas.

The questions raised by Mr Gray are interesting; in particular, that relating to transient performance of generating sets. The diesel performance was the subject of considerable discussion, since the engines are turbocharged and the criteria set by the specification were substantially higher than normal marine practice.

This is illustrated in Fig. D2. Referring to note (1), the momentary and permanent variations and the recovery time were required to be met also for full-load rejection and the load rejection which occurs on completion of the run-up of propulsion motors, with zero pitch on the propeller.

To minimize system disturbances, the voltage change of each main generator was specified not to exceed ± 15% under the most onerous conditions likely to occur in normal operation; and to recover and remain within ± 2.5% normal voltage in less than one second. The most onerous condition for this duty was considered to be the direct-on-line starting of a propulsion motor with four generators operating in parallel. All likely base loads were evaluated for this purpose.

In addition, the main generating sets were to be capable, when two sets were running in parallel, of starting a propulsion motor. In this case, there was no restriction on voltage dip except that circuit breakers and contactors were not to drop out and there was to be no related injurious effect on any equipment. In practice, both the engine and generator manufacturers fully met the performance required.

The DP computers are normally fed from a guaranteed power supply and only in the remotely possible instance of this failing would they be fed from a bypass supply on the ship's mains. Nevertheless, the computers and all their associated peripheral equipment were to accommodate both the normal supply variations and the following:

(a) Occasional voltage variations ± 20% recovering to within 5% in 10 seconds.
(b) Total harmonic distortion 10% rms.
(c) Randomly phased deviations of either polarity. These transients might be either common or series mode. Expected peak amplitudes, expressed as percentages of the supply rms voltage, were given as:

Amplitude + or −% of supply	*Duration in milliseconds*
100	10
200	1
300	0.02
500	0.005
1000	0.001

Digital techniques and multiplexing are used in a variety of applications on *Iolair*. Optical fibres are not used, as they were commercially in their infancy for this type of application at the design stage. They would doubtless be given serious consideration in future. With hindsight, multiplexing could have been used much more extensively to advantage. At the time, ensuring individual systems and plant security, together with possible problems of data corruption known to exist in other installations, prescribed hard wiring for control equipment generally.

Considerable efforts were made, both by specification and the electrical subcontractors, to avoid transmission or reception of electromagnetic interference (EMI). Once the quality assurance checks on the installation had been carried out and the computer installation commissioned, there were no EMI problems manifest. Indeed, on the whole installation, so far as we are aware, there have only been two problems caused by interference and, in one of these, the cause was inadvertant installation of an unscreened cable in circuits for which a screened cable had been specified. An EMI survey was also carried out on the vessel by Det norske Veritas; this did not highlight conclusively any area likely to cause problems.

In our opinion, the emphasis by Mr Gray on short-circuit testing is quite rightly made. We are not aware of any national standards which require prime movers to be capable of withstanding the short-circuit torques which may be imposed in case of fault.

The request to carry out such tests is frequently met at first with surprise, and sometimes resistance, by the prime-mover manufacturers. For *Iolair*, short-circuit tests were specified and carried out for main, standby and emergency combined sets.

In the case of the main generators, a three-phase short-circuit test was carried out in the manufacturer's works on one machine to confirm the electrical performance parameters. Subsequently, and on a different machine, a single-phase (line-to-line) short-circuit test was carried out on the combined set in the engine manufacturer's works. It is of interest to note that the engine-coupling design was significantly changed from the manufacturer's standard, to accommodate this design requirement.

The question from Mr Bailey appears to relate to *Iolair's* 'jeopardous role', during which the vessel might be called upon to assist a North Sea platform in event of a blowout, and during which hydrocarbon gases might be present.

The philosophy, in this instance, is that the vessel would not knowingly be taken into a gaseous atmosphere. If called to assist, the procedure is to close all non-essential ventilation openings and doors, all of which are monitored and gas-tight. A gas-detection alarm system monitors the presence of gas from some 70 detector positions; and, at the first-stage alarm level, all remaining ventilation openings are closed by remote operation.

In these circumstances, there is no clean air supply available and, clearly, the vessel can only continue to operate for a limited period. The habitability conditions were carefully established during trials. The main engines can continue to operate because their combustion air is ducted directly and certain design precautions are taken to ensure safe operation. A second-stage gas alarm provides warning that gas levels are approaching values which could lead to main-engine shutdown and that the vessel must be withdrawn to a safer environment.

The choice of electrical equipment in potentially hazardous areas was influenced by tanker experience but we accepted a need to adopt the area classification approach, in order to assure the most cost-effective and reliable design for this special-purpose ship.

In response to Mr Boddie, the design of the plant was very much by system. With this in mind, the supply of the major items of equipment was confined to one subcontractor, albeit some individual items were then subcontracted to other manufacturers. This was supplemented by the shipbuilder, major subcontractor and the owners' representatives undertaking a joint study to confirm the overall system performance. The complete design process was overseen by the shipyard and also the owners' representatives.

Problems did exist, as must be expected in a design of this nature. The division of disciplines within the shipyard, and their split responsibilities with regard to electrical equipment, occasionally caused problems for the shipbuilders' electrical co-ordinator, who had been set up especially to deal with this type of difficulty. Similar events occurred with other disciplines. This was mainly historical, in that both naval architects and machinery designers were responsible for packages which have electrical, mechanical and structural implications.

It is believed that this could be improved in future by adopting the idea of a project team, incorporating all disciplines with a collective responsibility, working from one office. This could be supplemented by improved quality-assurance procedures, ensuring at the earliest opportunity that the receipt of equipment supplied by the subcontractor fully met the specified requirements.

Taking this idea a stage further, the major subcontractors should be required to nominate and provide their own project leaders, to be responsible for the co-ordination of their equipment. This would improve the flexibility of contractors and subcontractors in responding to changes, inevitable in a specialist vessel as the detail design is developed.

However, it can be said that the design process of *Iolair* was largely successful and the system of having a main subcontractor and a co-ordinator within the shipyard contributed greatly towards its success.

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