MARITIME ELECTRICAL INSTALLATIONS

NOTES ON DESIGN REQUIREMENTS

A complete shipboard electric plant is similar to the electric power generating and distribution, and utilization system of a self contained shore-based industrial installation. Electric power is required for motors driving propulsion plant, propulsion plant auxiliaries and deck machinery, interior and exterior illumination, navigation lights, ventilation and air conditioning, stores and cargo refrigeration, electric heating, galley equipment, drinking water and sanitary systems, and casualty control machinery such as fire and bilge pumps. Power must also be supplied for interior communication systems, announcing and alarm systems, radio communication, radar, and other electronic aids to navigation.

For passenger vessels, the electric power requirements extend to hotel and recreation loads, theatre and dance floor lighting, restaurant and swimming pool equipment, motion picture projection, public address systems, and stewards call systems. For passenger and crew safety, the electric installation includes automatic fire detecting and alarm systems, power-operated watertight doors.

Electric power is vital to all shipboard operations and to the safety and comfort of the passengers and crew. For this reason, shipboard electric plants must contain equipment necessary to maintain continuity of service, since a vessel at sea is isolated from external sources of electrical energy. Therefore, standby ship service generating capacity, usually equal to the rating of one of the. ship service generators, is provided. In addition, one or more, sources of emergency power, designed to automatically assume load upon loss of ship service power, are required to supply those loads that are necessary for the safety of the passengers and crew; the emergency source of power should also have additional capacity adequate to supply those loads vital to getting the propulsion plant and ship service generators back in service. Quick-starting diesel generators are usually provided for emergency power; however, storage batteries or gas turbine driven generators are satisfactory for this service. Emergency storage batteries combined with motor generator sets are required on passenger vessels to provide temporary emergency power to certain vital loads until the emergency generator can start and assume the entire emergency load.

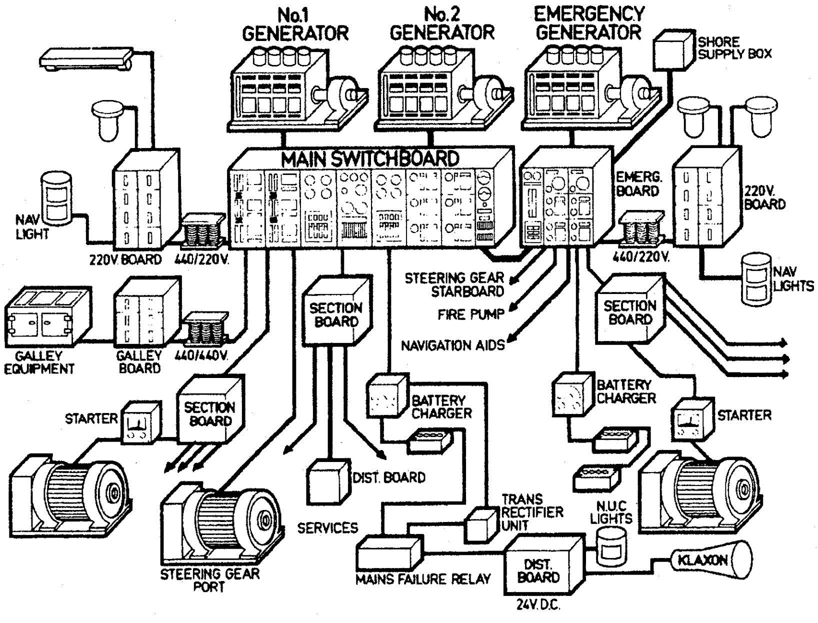
To avoid prolonged shutdown at sea, adequate spare parts should be stowed aboard ship to replace vital parts which are subject to wear and breakdown. It follows that adequate detail drawings and manuals containing instructions for operation, repair, and adjustment also should be placed aboard ship.

For greater dependability at sea, electric equipment necessary for the operation of the vessel is required to have certain marine features such as dependable operation during rolling and pitching of the vessel, mechanical parts resistant to shipboard vibration, and windings and hardware resistant to moisture and corrosion.

A shipboard electric plant includes: generating equipment; switchgear for control of the generators and distribution of power; and distribution panels, transformers, motor generators, and bus transfer equipment as necessary to provide the proper type of power to electrical loads[1].

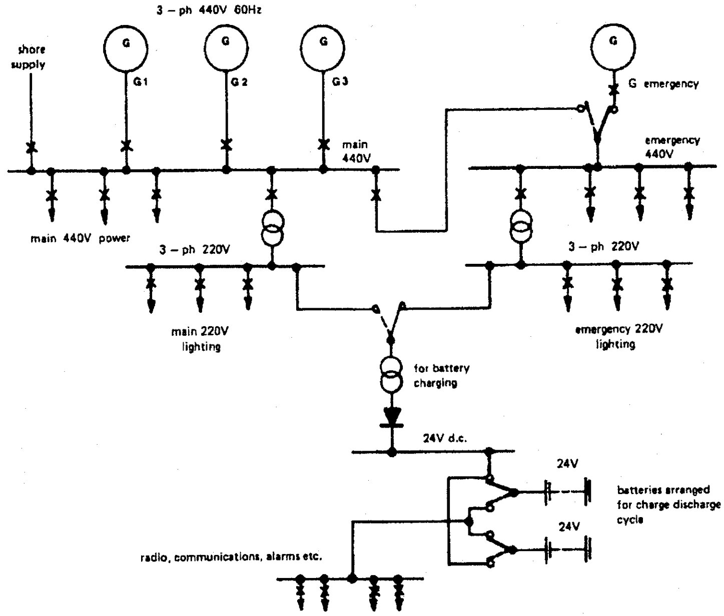
Rules and regulations dictate the minimum requirements of a ship based electrical installation. Minimum acceptable standards are issued by various bodies including national governments, international conventions (such as SOLAS), international standards associations and classifications societies such as DNV. The main objective of rules for electrical installations is to ensure that the power system is designed, built and installed so that it provides a safe and reliable installation with respect to availability, operator/user safety and a minimum risk of fire hazards [2].

The major sub-systems of a ship's electrical installation are shown in the general diagram below [3].



[*Practical Marine Electrical Knowledge – Hall]*

One of the documents required for approval of the system design is the **single line diagram** which provides an overview of major sub-systems or even the entire electrical installation. A single line diagram for an entire electrical installation is shown below.



[*Practical Marine Electrical Knowledge – Hall]*

The vast majority of ships have an alternating current (ac) distribution system in preference to a direct current (dc) system. An ac network is cheaper to install and operate than a dc system. In particular, ac offers a higher power/weight ratio for the generation, distribution and utilisation of electricity. Simple transformers efficiently step up or step down ac voltages where required. Three phase ac is effectively converted into rotary mechanical power in simple and efficient induction motors. A ship's electrical distribution scheme generally follows shore practice. This allows normal industrial equipment to be used on board ship after being 'marinated', where necessary, to withstand the rigours of a sea life (e.g. it must withstand the vibration, humidity, high temperature, ozone, sea water, etc. found in various parts of the ship).

The majority of ships have a 3 phase, 3 wire, 440V insulated neutral system. This means that the neutral point of star connected generators is not earthed to the ship's hull. For Continental European vessels, a 380V, 3 phase system is common.

Ships with very large electrical loads have generators operating at high voltages (HV) of 3.3kV and even 6.6kV. Such high voltages are economically necessary in high power systems to reduce the size of current, and hence reduce the size of conductors required. Ships operating at such high voltages are still quite rare, but offshore oil and gas production platforms operate at up to 13.8 kV, where equipment weight saving is important. Distribution systems at these high voltages usually have their neutral points earthed through a resistor to the ship's hull.

The frequency of an ac system can be 50Hz or 60Hz. 50 Hz is a European standard frequency and 60 Hz is a US standard frequency. 60 Hz is the most common frequency adopted for use on board ship; the higher frequency enabling motors and generators to run at higher speeds with a consequent reduction in size for a given power rating.

Lighting and low power single phase supplies usually operate at the lower voltage of 220V although 110V is also used. These voltages are derived from 'step down' transformers connected to the 440V system.

Major electrical sub-systems on the one line diagram are described briefly below.

MAIN GENERATORS

The main generators have a capacity such that in the event of any one generating set being stopped it will still be possible to supply those services necessary to provide normal operational conditions of propulsion and safety. Minimum comfortable conditions of habitability shall also be ensured which include at least adequate services for cooking, heating, domestic refrigeration, mechanical ventilation, sanitary and fresh water.

For vessels propelled by electric power and having two or more constant voltage propulsion generating sets, the ship's service electric power may be derived from this source and additional ship's service generators need not be fitted provided that with one propulsion generator out of service, effective propulsion can be maintained.

A generator driven by a main propulsion unit (shaft generator) which is intended to operate at constant speed, e.g. a system where vessel speed and direction are controlled only by varying propeller pitch, may be considered to be one of the required generators.

Each main generator (ac generators are also called alternators) has its own circuit breaker between the generator output and main switchboard bus bars.

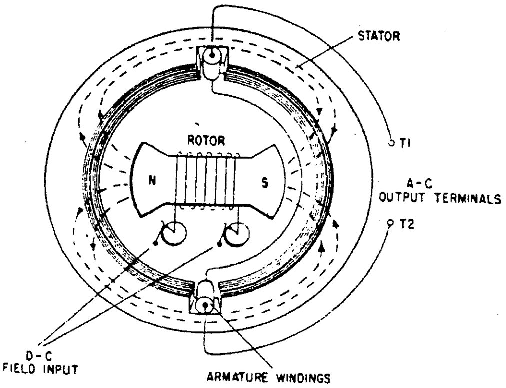
There are various types of alternating current generators utilized today. However, they all perform the same basic function. The types discussed below are typical of those must widely used in modern electrical equipment.

Revolving Armature

In the revolving armature a.c. generator, the stator provides a stationary electromagnetic field. The rotor acting as the armature, revolves in the field, cutting the lines of force, producing the desired output voltage. The major limitation of this design is that the output power is passed through sliding contacts (sliprings and brushes). These contacts are subject to frictional wear and sparking. In addition, they are exposed, and thus liable to arc over at high voltages. Nevertheless the revolving armature may be found in some marine generators, this arrangement often forms the exciter providing the main field current for brushless alternators. Slip rings are not required when used as the exciter in a brushless alternator.

Revolving Field

The revolving field a.c. generator is by far the most widely used type. In this generator, direct current from a separate source is passed through windings on the rotor. This maintains a rotating electromagnetic field of fixed polarity (similar to a rotating bar magnet). The rotating bar magnetic field moves with the rotor, extends outwards and cuts through the armature windings embedded in the surrounding stator. As the rotor turns, alternating voltages are induced in the windings since magnetic fields of first one polarity and then the other cut through them. Since the output power is taken from stationary windings, the output may be obtained from fixed terminals. A simplified diagram of the rotating field alternator is shown below.



Rating of a.c. generators

The rating of an a.c. generator refers to the load it is capable of supplying. The normal load rating is the load it can carry continuously. Its overload rating is the above normal load which it can carry for specified lengths of time only. The load rating of a particular generator is determined by the internal heat it can withstand. Since heating is caused mainly by current flow, the generator's rating is identified very closely with its current capacity. A review of three phase power definitions is contained in Appendix 1.

The maximum current that can be supplied by an a.c. generator. depends upon (i) the maximum heating loss (I^2R power loss) that can be sustained in the armature and (ii) the maximum heating loss that can be sustained in the field. The armature current varies with the load. This action is similar to that of d.c. generators. In a.c. generators, however, the lagging power factor loads tend to demagnetize the field and terminal voltage is maintained only by increasing the d.c. field current. Therefore, a.c. generators are rated in terms of load current and voltage output, or kilovolt-ampere (kVA) output, at a specified frequency and power factor. The specified power factor is often 80 percent lagging. For example, a single phase a.c. generator designed to deliver 100 amperes at 1,000 volts is rated at 100 kVA. This machine would supply a 100 kW load at unity power factor or a 80 kW load at 80 percent power factor. If the a.c. generator supplied a 100 kVA load at 20 percent power factor, the required increase in d.c. field current needed to maintain the desired terminal voltage would cause excessive heating in the field.

A cargo vessel may have two main generators typically rated between 400 kVA to 1200 kVA, supplying a 440V, 60Hz three phase voltage.

Construction

The stator, or armature, of the revolving field a.c. generator is built up from steel punchings, or laminations. The laminations of an a.c. generator stator form a steel ring that is keyed or bolted to the inside circumference of a steel frame. The inner surface of the laminated ring has slots in which the stator. winding is placed.

There are two main types of rotor construction. The first type is the salient pole rotor in which the required excitation of the machine is produced by individual projecting poles each of which is wound with its own field coil. The second type, the non salient pole is fitted with a cylindrical steel rotor in which coils are fitted to provide the necessary pole configuration.

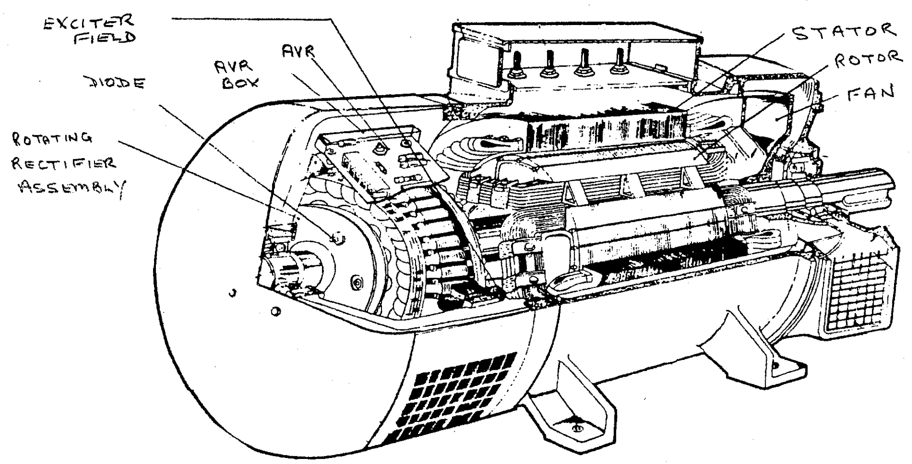
Most engine driven alternators use salient pole construction. There is an inverse relationship between the number of poles on the rotor and the generator driven speed for a specified output frequency. The relationship is:

$$\mathit{frequency} \quad = np/120 \qquad Hz$$

where: n is the speed of the rotor in rpm
p is the number of poles on the rotor

From the above it can be determined that for a 50Hz output at 750, 1000, 1500 rpm, 8, 6 and 4 pole rotor systems are required respectively, whilst for 60Hz operation the prime mover speed would have to be increased by 20%. Also the specific output of the a.c. generator increases with operating speed, which means that for a given electrical output an 8 pole machine would be larger that a 4 pole machine.

A 250 kVA alternator is shown below. The specifications for this machine are contained in Appendix 2.



The main field is of the salient pole construction with four poles. The excitation for this rotating field is derived from a smaller ten pole generator which is of the revolving armature type mounted on the same shaft. Control of the main rotating field is achieved by changing the field current in the exciter. Also visible on the pole faces are the damper or amortisseur (literally 'killer') windings which are similar to the bars of a squirrel cage rotor. These windings are present to reduce the hunting above and below synchronous speed which result from the prime mover not having uniform speed over one complete revolution. When the poles are rotating past the armature at synchronous speed no voltage is induced into these short circuited windings. If however the rotor increases or decreases its speed above or below the synchronous value a voltage and large current flows in the damper winding which by Lenz's Law will oppose the force that produced it, that is the speed variation.

Enclosure protection for electrical equipment is defined in terms of the protection afforded against the ingress of solid particles and liquids. A two or three figure number such as IP15 is used to indicate the amount of protection of the enclosure. The IP Code is contained in Appendix 3.

A typical design specification for a cargo ship is included as Appendix 4.

MAIN SWITCHBOARD

Switchgear and control gear assembly for the control of a ship's service power generated by the main source of electrical power and its distribution to all electrical consumers.

A typical installation with 3 x 800 KVA generators consists of 16 individual panels each with a specific function.

1 panel with circuit breaker and protection equipment for each generator.
1 synchronising panel for paralleling each alternator.
4 x 415 volt feeder panels.
8 group starter panels for control of motor circuits (these may not necessarily be part of the main switch board).

The entire switchboard is of dead front construction and has a vibration proof framework constructed of angle steel with steel panels of 3.2mm. The complete set of 16 panels is about 8.5m long. Switchboard design/specification for a cargo ship is also contained in Appendix 4. A line diagram for the MSB of a cargo ship with three generators is shown in Appendix 5.

EMERGENCY GENERATOR AND SWITCHBOARD

A generator forming a self contained emergency source of electrical power. This emergency source of electrical power, associated transforming equipment, if any, transitional source of emergency power, emergency switchboard and emergency lighting switchboard shall be located above the uppermost continuous deck and shall be readily accessible from the open deck. They shall not be located forward of the collision bulkhead, except where permitted by the Administration in exceptional circumstances. The location of the emergency source of electrical power, associated transforming equipment, if any, the transitional source of emergency power, the emergency switchboard and the emergency lighting switchboard in relation to the main source of electrical power, associated transforming equipment, if any, and the main switchboard shall be such as to ensure that a fire or other casualty in the space containing the main source of electrical power and switchboard will not interfere with the supply and distribution of emergency power. A summary of the emergency requirements and the layout of an emergency switchboard is contained in Appendix 5.

PROTECTION EQUIPMENT

Electrical installations must be protected against accidental overcurrents up to and including short circuit by appropriate devices. Continuity of service through discriminative action of the protective devices is required.

Devices are normally provided for overload protection (current above rated value) and short circuit protection (current many times the rated value). Discrimination ensures that the protective device nearest the fault is used to remove the supply.

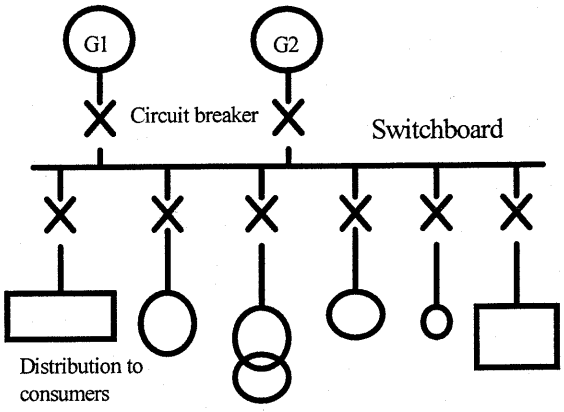
References

1. *Marine Engineering, Harrington R.L (Ed)*
2. *D.N.V. Germany, Web site.*
3. *Practical Marine Electrical Knowledge, Hall D T.*

DISTRIBUTION SYSTEMS

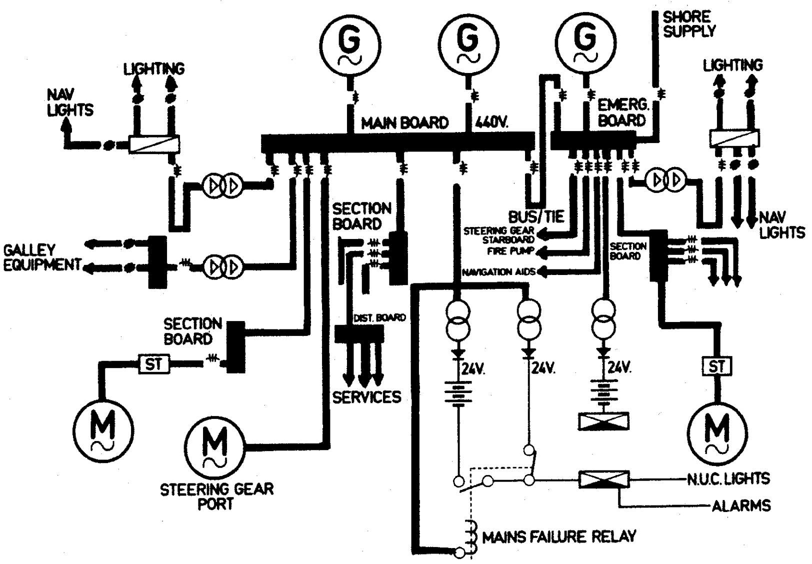
The distribution system, as the name implies is the method by which the electrical energy produced by the ship's generators is fed around the vessel to all the individual loads.

A simple distribution system is shown below



A generated voltage of 440 volts may be fed to large motors and other loads directly, whereas many other loads require a lower voltage and this is usually obtained through the use of three phase step down transformers.

A more detailed arrangement of a ship's distribution system is shown below.



[Practical Marine Electrical Knowledge – D Hall]

Outgoing circuits from a main switchboard are shown in drawing M2-3731 in Appendix 6.

In any distribution system there are four components:

- source of power;
- transmission system;
- load or consumer of power; and
- a control system.

The alternators will feed into a main switchboard via circuit breakers, thus providing protection and enabling them to be isolated from the board, if required. The main switchboard will act as the distribution centre for the power requirements of the vessel. From the switchboard, power will be supplied to the various loads via individual circuits.

Each circuit will have its own circuit breaker / isolating device, protection devices (eg. overload relay or fuse), cables, and load.

Some outputs from the main board will supply smaller boards around the ship for local distribution. These smaller boards are called distribution boards. This reduces the amount of cables that have to run from the main switchboard. It is only required to run one set of large cables to the local distribution board. Further division and distribution is cried out from that point.

Voltage

With ac. systems three -phase distribution with an insulated neutral is still commonly employed. On medium voltage systems 440 V is usually the selected preference to 380 V because the former can result in significant economic savings due to the smaller copper sizes required. However, distribution at 415 V is sometimes used when ships have a large hotel load as this provides a line to neutral voltage of 240 V and enables standard domestic equipment and fittings to be employed. Such a system would use. four wires with the neutral earthed but without hull return. At 3.3 kV a three wire system with the neutral earthed through a resistor is normally employed.

Frequency

The two common power frequencies in use throughout the world are 50Hz and 60Hz. The frequency selected for a particular application may often be determined by the shore supplies available. For example ships continuously operating around Australia would use 50Hz. Where a choice exits the advantages usually favours the higher frequency.

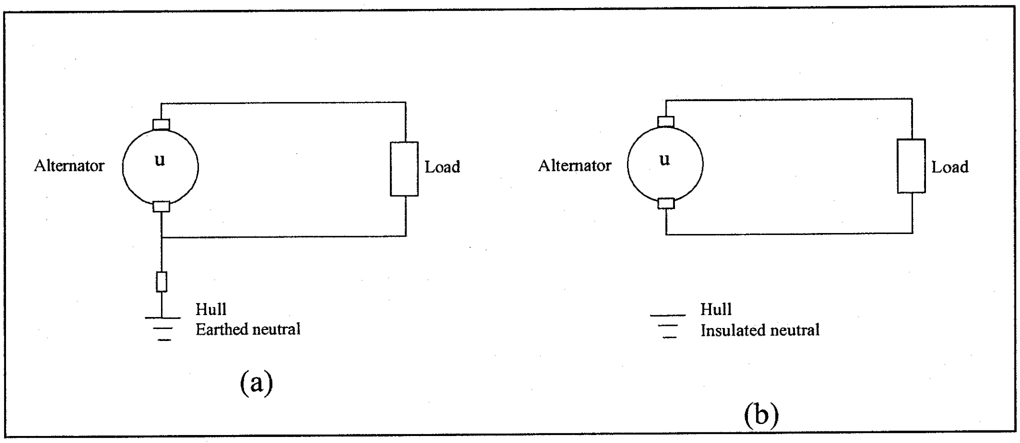
The power output of a motor is proportional to its speed and therefore a 60 Hz machine will generally be more compact and have a greater power to weight ratio than its 50 Hz equivalent. Less iron is required at 60 Hz and this results in a cheaper machine.

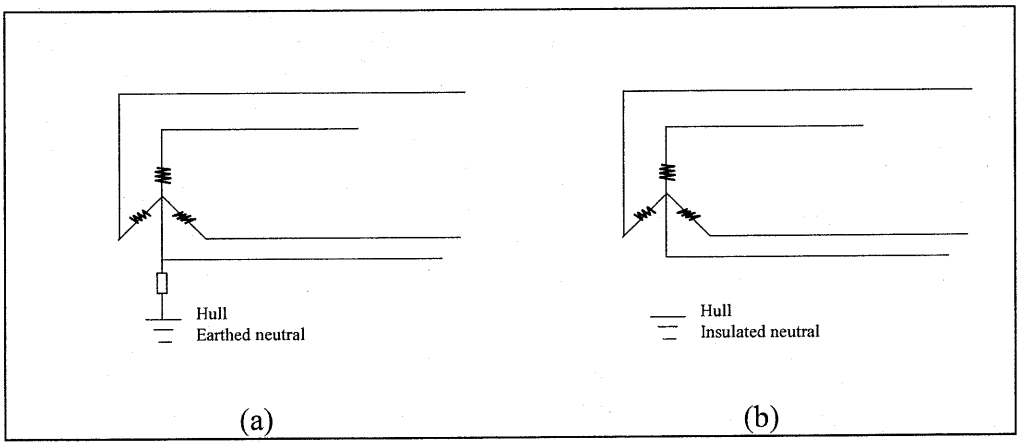
Where a shore supply is taken it is permissible to supply a 60Hz system at 50Hz provided the voltage is reduced. Thus, ideally 440V 60Hz motors should be supplied at 380 V when only a 50Hz supply is available. At 415 V 50 Hz the same motors will run with a slightly greater temperature but, provided that the ambient temperature is not too high, it is unlikely that any damage will result. It must be accepted that induction motor speeds will be reduced by about 20%.

The operation of a 50 Hz system from a 60Hz supply is not to be recommended. The motors will run faster and therefore will produce more torque. In doing so they will demand more than their rated current and could be severely overloaded.[4]

Neutral Earthing

With very few exceptions marine electrical design engineers favour the insulation of the neutral on medium voltage systems although this is contrary to the normal practice ashore.





Insulated neutral systems are primarily adopted to avoid the risk of loss of essential services, such as steering gear and vital engine room auxiliaries in the even of an earth fault. With solid neutral earthing a phase to earth fault constitutes a short circuit on the phase concerned and causes the operation of protection equipment which will trip the circuit breaker.

Protection of outgoing circuits

Whilst the generators are usually protected by air circuit breakers (ACB's), the outgoing distribution circuits to essential and non essential loads are protected by either moulded case circuit breakers (MCCB's), miniature circuit breakers (MCB's) or fuses.

In moulded case circuit breakers the insulated moulded housing forms an integral part upon which are mounted the various components. The operating parts are generally inaccessible for maintenance. Current ratings vary from 100A to about 2000A. The manufacturer usually markets these units in various frame sizes. For each frame size (physical size) there are a range of current ratings.

A miniature circuit breaker is the type of breaker found in section and distribution boards. The current rating is usually less than 100A.

Generally a fuse has:

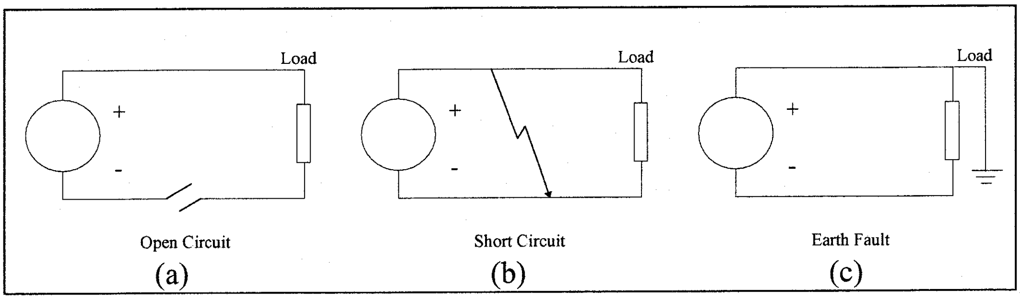
- A fault rating which is equal to or greater than the system fault level at the point of application.
- A current rating to provide adequate protection to the circuit.
- A current rating to provide discrimination to downstream protective circuits.

Discrimination is achieved when only the protective device immediately upstream of a fault operates, all other circuits remain in operation. This arrangement ensures that healthy circuits continue to operate, whereas the faulty circuit is removed from service.

Faults

An **open circuit fault** is when a cable or connection separates, breaks, or fails. This causes an interruption to the flow of the current and therefore, stops the equipment from operating. If the equipment is essential for the running or safety of the vessel, this could result in a serious situation.

In addition, loose wires or connections can come in contact with other objects or personnel, resulting in danger due to arcing and electrocution.



Open Circuit (a) Short Circuit (b) Earth Fault (c)

A short circuit fault occurs when two conductors (wires) supplying a load come in contact with each other. This causes a direct flow of current from one to the other resulting in an extremely high current.

For example, consider a load being supplied by a 240 V power source. The resistance of the load is 24 Ω, and the resistance of the electrical cable supplying the load is 0.2 Ω. Therefore, the current flowing is obtained from the above equation as:

$$I = \frac{V}{R} = \frac{240}{24+0.2} = \frac{240}{24.2} = 9.92\text{Amps}$$

Now if a short occurs across the wires, then the current will by-pass the load and the new current flow will be:

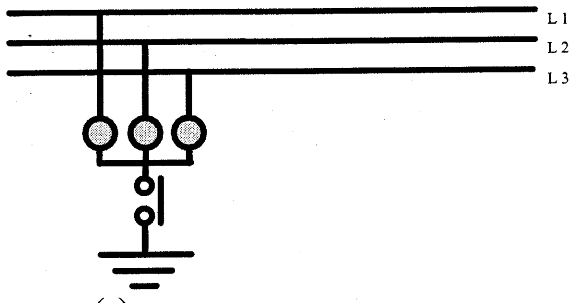
$$I = \frac{V}{R} = \frac{240}{0.2} = 1200\text{A}$$

This high current level creates a fire hazard and should be removed as soon as possible.

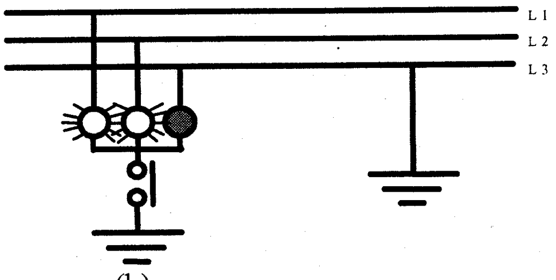
The **earth fault** is when one of the power lines comes in contact with the hull of the vessel. If the vessel has an earthed neutral, then this will cause a fuse to blow or circuit breaker to trip. However, most vessels have insulated neutrals, and these systems will continue to operate, in spite of the earth fault. If a second earth fault occurs on another line in the vessel, a short circuit current can occur from the first fault to the second via the ship's hull.

Vessels with an insulated neutral are usually fitted with earth fault indicating instrumentation to identify the presence of an earth fault.

Earth fault indicators can be a set of lamps or an instrument calibrated in kΩ to show the resistance to earth. An earth fault lamp installation for a 3 phase system is shown below.



(a)



(b)

In (a) the system is healthy, (ie. no earth faults). Thus the three lamps will glow with **equal half brilliance.** This is because there are two lamps in series across each set of lines. If an earth fault occurs on one line, Figure (b), the lamp connected to the line with the earth fault will **dim**, while the other lamps will **glow brighter**. This is since the voltage of the faulty line and the hull is now the same, (due to the earth fault). However, the others have a single lamp across the lines.

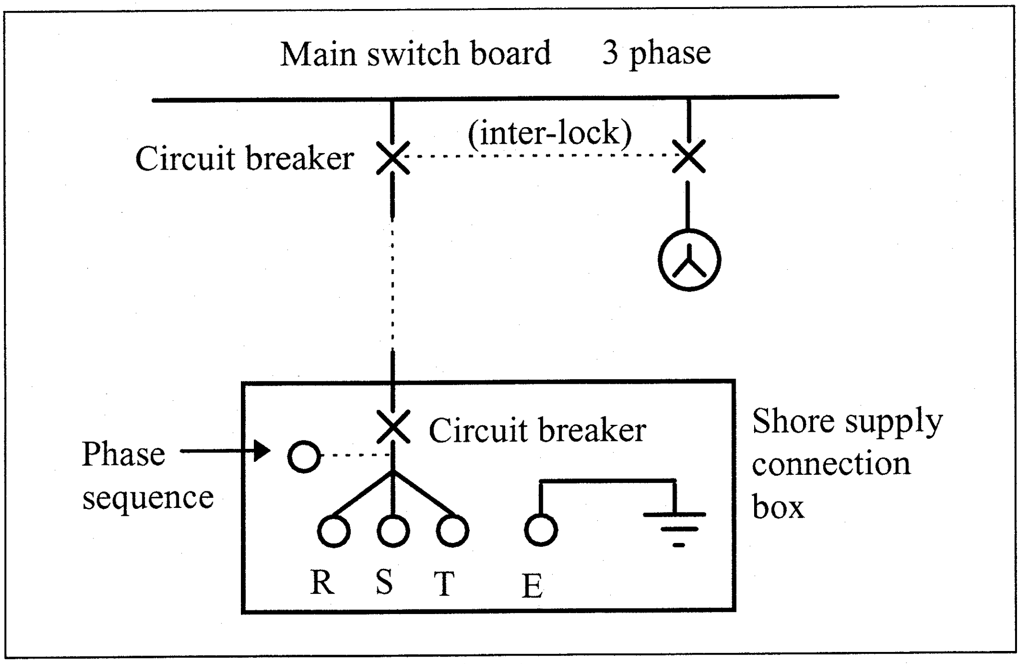
Shore Power

A shore power supply to the vessel is sometimes required due to:

- all of the ship's alternators are shut down for overhaul or maintenance;
- unable to run the alternators when dry docked or slipped; or
- during long periods of lay up adjacent to a wharf.

A shore connection box is installed to accept the shore supply cable, and usually consists of:

- Terminals or an appropriate socket to accept the shore supply cable.
- An earthing terminal to earth the ship's hull to the shore
- A phase sequence indicator. This indicates the shore supply phase sequence. A wrong shore supply phase sequence will mean that the motors will run in reverse.

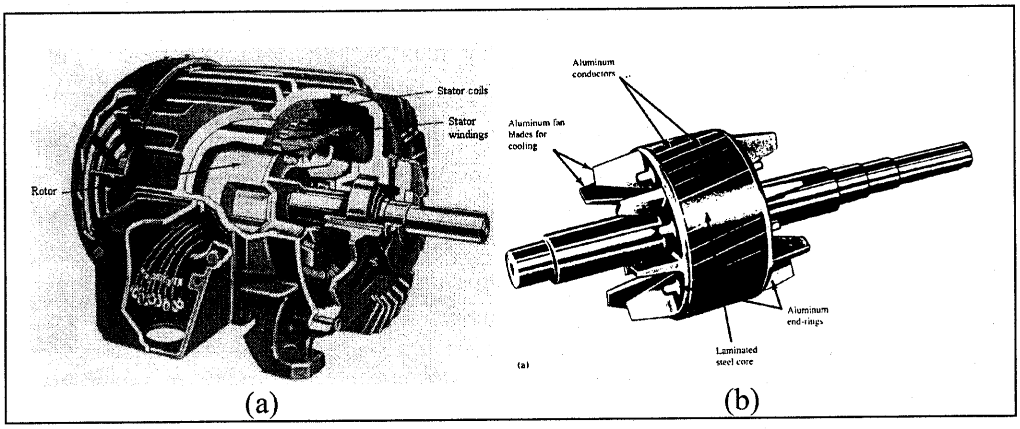


Typical Shore Connection Arrangement

Motors

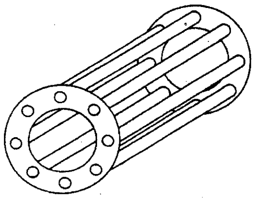
The drive power for compressors, pumps, and fans aboard vessels are usually supplied by electric motors. The most common type of motor is the **three phase induction** motor. There are other types of motors used on board such as single phase induction motors and three phase synchronous motors.

An induction motor has two main components, i.e. the stator and the rotor. The stator Figure (a) carries the three phase winding in slots cut into a laminated steel magnetic core. The ends of the stator windings are terminated in the stator terminal box, where they are connected to the incoming cable from the three phase supply.



(a) (b)

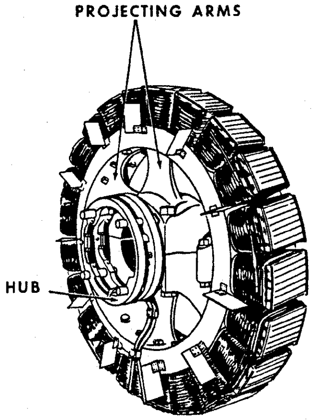
The rotor Figure (b) has a “squirrel cage” winding. This consists of conductor (copper or aluminium) bars connected together at the ends by “end rings”. The conductor bars are set in a laminated steel magnetic core. The conductor bars are of the form:

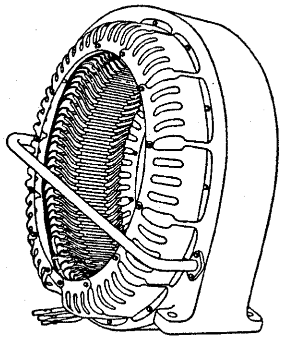


When the three phase supply is connected to the stator windings, the currents which flow in the windings produce a rotating magnetic field. This rotating field sweeps past the bars of the rotor cage thus inducing voltages (and hence currents) into them. The rotor currents produce their own magnetic field which interacts with the stator field resulting in the rotor following the rotating field of the stator. The rotor must turn at a speed slightly less than the stator field otherwise there would be no ‘cutting’ action of stator field on rotor cage. The speed of stator field is called the synchronous speed. The difference between rotor speed and stator field speed is called the slip speed of the machine.

The induction motor is the most commonly used a.c. motor. It is simple in construction and principle of operation. It has excellent speed /torque characteristics with full load slip is about 5% of synchronous speed.

In a three phase **synchronous motor** the squirrel cage rotor is replaced with a wound rotor which effectively becomes a rotating electromagnet. The magnetic field of the rotor is due to a d.c. excitation current supplied via slip rings or through a brushless arrangement. The rotor magnetic field 'locks in' with the rotating stator field resulting in a fixed speed machine.





[Taken from Motors and Controls- J Humphries]

ELECTRIC PROPULSION

[Taken from Practical Marine Electrical Knowledge – D Hall]

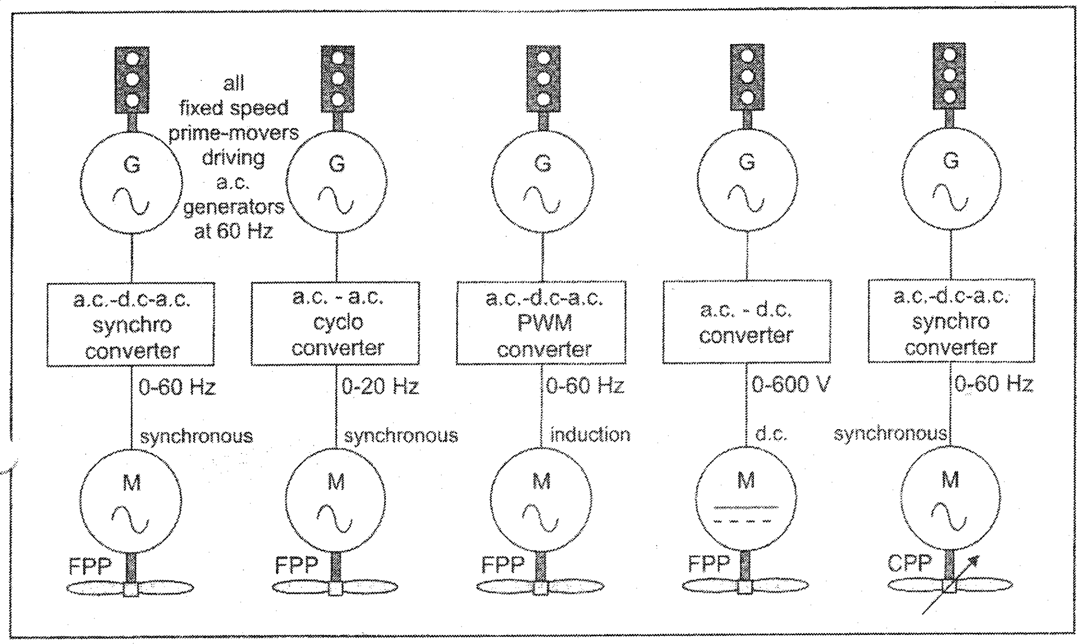


Fig. 8.3 Electric propulsion options.

For very high power, the most favoured option is to use a pair of high efficiency, high voltage a.c. *synchronous motors* with fixed pitch propellers (FPP) driven at variable speed by *frequency control* from electronic converters. A few installations have the combination of controllable pitch propellers (CPP) *and* a variable speed motor. Low/medium power propulsion (1-5 MW) may be delivered by a.c. *induction motors* with variable frequency converters or by d.c. motors with variable voltage converters.

The prime-movers are conventionally constant speed *diesel engines* driving a.c. generators to give a fixed output frequency. Gas turbine driven prime-movers for the generators are likely to challenge the diesel option in the future.

Conventionally, the propeller drive shaft is directly driven from the propulsion electric motor (PEM) from inside the ship. From experience obtained from smaller *external* drives, notably from ice-breakers, some very large propulsion motors are being fitted within rotating *pods* mounted outside of the ship's hull. These are generally referred to as *azipods,* as shown in Fig. 8.4, as the whole pod unit can be rotated through 360 degrees to apply the thrust in any horizontal direction, i.e. in *azimuth.* This means that a conventional steering plate and stern side-thrusters are not required.

Ship manoeuvrability is significantly enhanced by using azipods and the external propulsion unit releases some internal space for more cargo/passengers while further reducing hull vibration.

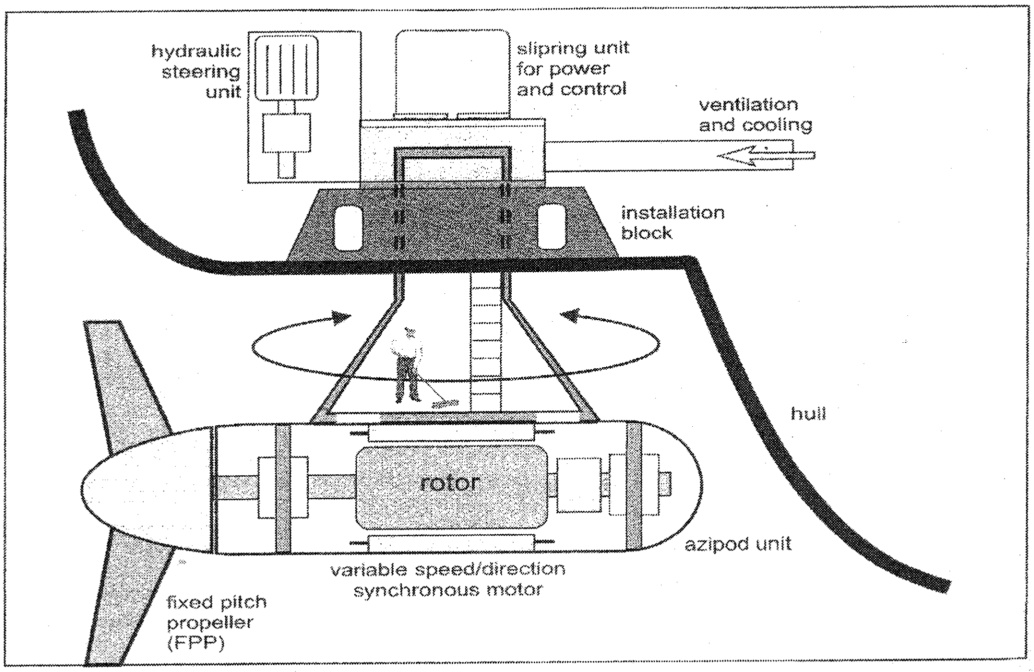


Fig. 8.4 Azipod drive unit.

Power Supply Network

As the demand for electrical power increases on ships (particularly passenger ferries, cruise liners, and specialist offshore vessels and platforms) the supply current rating becomes too high at 440 V. To reduce the size of both steady state and fault current levels, it is necessary to increase the system voltage at high power ratings.

Note: In marine practice, voltages below 1000 V are considered LV (low voltage). HV (high voltage) is any voltage above LV. Typical marine HV system voltages are 3.3 kV or 6.6 kV but 11 kV is used on some offshore platforms and specialist oil/gas production ships e.g on some FPSO (floating production, storage and offloading) vessels.

By generating electrical power at 6.6 kV instead of 440 V the distribution and switching of power above about 6 MW becomes more manageable.
The component parts of an HV supply system are now standard equipment with HV diesel generator sets feeding an HV main switchboard. Large power consumers such as thrusters, propulsion motors, air-conditioning (A/C) compressors and HV transformers are fed directly from the HV switchboard.

An economical HV system must be simple to operate, reasonably priced and require a minimum of maintenance over the life of the ship. Experience shows that a 9 MW system at 6.6 kV would be about 20% more expensive for installation costs. The principal parts of a ship's electrical system operated at HV would be the main generators, HV switchboard, HV cables, HV transformers and HV motors. An example of a high voltage power system is shown in Fig. 8.6.

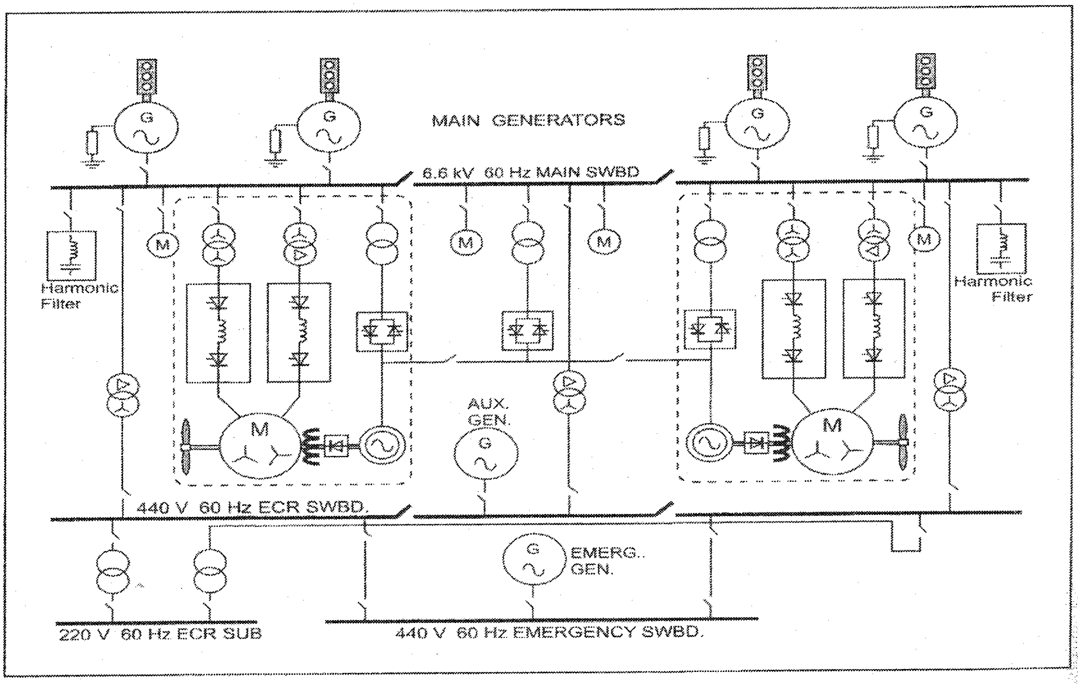


Fig. 8.6 HV power system.

In the example shown the HV generators form a central power station for all of the ship's electrical services. On a large passenger ship with electric propulsion, each generator may be rated at about 10 MW or more and producing 6.6 kV, 60 Hz three-phase a.c. voltages.

The principal consumers are the two synchronous a.c. propulsion electric motors (PEMs) which may each demand 12 MW or more in the full away condition. Each PEM has two stator windings supplied separately from the main HV switchboard via transformers and frequency converters. In an emergency a PEM may therefore be operated as a half-motor with a reduced power output.

A few large induction motors are supplied at 6.6 kV from the main board with the circuit breaker acting as a direct-on-line (DOL) starting switch.

These motors are:

- Two forward thrusters and one aft thruster, and
- Three air conditioning compressors

Other main feeders supply the 440V engine room sub-station (ER sub) switchboard via step-down transformers. An interconnector cable links the ER sub to the emergency switchboard. Other 440V sub-stations (accommodation, galley etc.) around the ship are supplied from the ER sub. Some installations may feed the ships sub stations directly with HV and step-down to 440V 1ocally.

ELECTRICAL EQUIPMENT IN HAZARDOUS AREAS

Electrical equipment which is intended to be used in areas that are classified as hazardous locations should be approved safe and listed by a certifying authority.

A hazardous area is defined as an area which an explosive atmosphere is present, or may be expected to be present, in quantities such as to require special precautions for the construction, installation, and use of potential ignition sources.[5]

The installation of electrical equipment in areas containing flammable gas or vapour and/or combustible dust, is to be minimized as for as is consistent with operational necessity and the provision of lighting, monitoring, alarm or control facilities enhancing the overall safety of the ship.[6]

To ensure 'safe' operation different methods of protection are used and they can be summarized as follows:

(a) *Exclusion:* This method involves the exclusion of the hazardous material, either gas or dust, from the apparatus so that a spark or hot surface inside the apparatus cannot cause ignition. This is achieved by sealing the apparatus enclosure, by the use of enclosed devices or by filling the apparatus with some substance, which may be solid, liquid or inert gas.

(b) *Explosion containment:* This method aims to contain an explosion, if it does occur, in the apparatus. A flameproof enclosure is probably the best known and most widely used of all techniques, but it is only appropriate for gas hazards.

(c) *Energy limitation:* This method uses energy limitation. Flammable gases and combustible dusts have minimum ignition energies, below which it is not possible for an arc or spark to cause an explosion. If the energy in an electrical circuit can be maintained below these levels, it cannot cause an explosion. Intrinsic safety is the most common technique used to achieve this.

(d) *Dilution:* This method involves dilution of a hazardous gas atmosphere below the lower flammable limit by ventilation. It is not appropriate for combustible dust areas.

(e) *Avoidance of' ignition source:* This method aims to prevent an ignition source from occurring. The most common technique is increased safety. This is used for apparatus or parts of apparatus, such as terminal boxes, that do not are or spark in normal service.

Safe types of electrical equipment commonly found aboard ship are as follows:

Intrinsically safe **Ex i**
This equipment uses energy limitation to provide protection. There are two categories of intrinsically safe electrical apparatus *ia* and *ib*. Essentially *ia* involves the application of more arduous testing conditions and provides a higher confidence of safety.

Increased safety **Ex e**
This equipment uses the avoidance of ignition source to provide protection.

Non Sparking **Ex n**
Similar to Ex e but not as exacting and therefore more restrictive in application.

Flameproof **Ex d**
This equipment uses the containment method to provide protection.

Pressurized enclosure **Ex p**
This equipment uses the exclusion method to provide protection.

Powder filled **Ex q**
This equipment uses the exclusion method to provide protection

On tankers areas are classified as 'dangerous spaces' or 'normally safe' spaces. The degree of hazard presented by a dangerous space is determined by the flammable nature of the cargo being carried.

Some or the particular requirements for electrical equipment installed on tankers is described below.[6]

Dangerous zones or spaces are:

(a) Spaces containing flammable cargo and all zones or spaces adjacent to cargo tanks are regarded as dangerous zones or spaces.

(b) An enclosed or semi-enclosed space with direct access into a dangerous zone or space is regarded as a dangerous space.

(c) An enclosed space located in a dangerous zone or space may be regarded as a non-dangerous space, provided that it is separated from the flammable liquid cargo by not less than two gastight steel bulkheads or decks, is mechanically ventilated and, in addition, has no direct opening into a dangerous zone or space.

Semi-enclosed spaces

Semi-enclosed spaces are considered to be spaces limited by decks and/or bulkheads in such a manner that the natural conditions of ventilation are sensibly different from those obtained on open deck, e.g. centre castle space.

The relevant gas group and temperature classfor the safe type equipment are IIA T3.

Cargo tanks

Intrinsically safe electrical equipment.

Cofferdams adjoining cargo tanks

Intrinsically safe electrical equipment.

Electric depth-sounding devices hermetically enclosed, located clear of the cargo tank bulkhead, with cables installed in heavy gauge steel pipes with gastight joints up to the main deck.

Cargo pump rooms

Intrinsically safe electrical equipment.

Lighting. Pump rooms immediately adjoining an engine room or similar non-dangerous space may be lit through permanently fitted glass lenses or ports fitted in the bulkhead or deck so arranged as to maintain integrity of the structure. The externally mounted lighting fixture may be designed so that the gastight flanged port forms part of the fixture. The lighting fixtures and wiring are to be located in the non-dangerous space. Alternatively, flameproof lighting fittings (symbol d) may be fitted. The fittings are to be arranged on at least two independent final branch circuits to permit light from one circuit to be retained while maintenance is carried out on the other.

Motors. Electric motors driving equipment located in cargo pump rooms are to be separated from the pump room by a gastight bulkhead or deck. Flexible couplings or other means of maintaining alignment are to be fitted in the shafts between the motors and the driven unit. In addition, suitable stuffing boxes are to be fitted where shafts pass through gastight bulkheads or decks.

Enclosed or semi-enclosed spaces immediately above cargo tanks or having bulkheads above and in line with cargo tank bulkheads
Irinsically safe equipment.
Safe type lighting fittings.

Electrical equipment other than stated above may be installed in 'tween deck spaces, provided that such equipment is housed in a mechanically ventilated compartment having access solely from the deck above, and of which the floor is separated from the cargo tanks by a cofferdam and the boundaries are oiltight and gastight with respect to the cofferdam and the 'tween deck spaces.

Compartments for cargo hoses
Intrinsically safe equipment.
Safe type lighting fittings.

Spaces under cargo tanks (e.g. duct keels)
Intrinsically safe equipment.
Flameproof lighting fittings (symbol d).
Lighting fittings of the air driven type.

Zones on open deck within 3 m of any cargo oil tank outlet or vapour outlet (e.g. cargo tank hatches; sight ports; tank cleaning openings; ullage openings; sounding pipes; cargo pump rooms and cofferdams; cargo pump room entrances)

Safe type equipment which is to be suitably protected for use on deck.

Zones on open deck over all cargo tanks (including all ballast tanks within the cargo tank area) to the full width of the vessel, plus 3 m fore and aft on open dock, up to a height of 2,4 m above the dock

Safe type equipment which is to be suitably protected for use on deck.

VESSEL DOCUMENTATION

Vessel Electrical Specifications.
An extract of a specification is shown in Appendix 4.

One line diagrams.
A full set of diagrams MSB, ESB and distribution system.

Schematic diagrams.
As contained in Appendix 6.

Electrical Load Documentation.
In order to determine the correct aggregate rating of the generators it is necessary to determine the electrical loading that will be experienced under various operating conditions.

There are three ways to ascertain the electrical load on the generators. These are empirical formulas; simulation and electrical load analysis. In a design process, the first estimate of electrical load is often made using empirical formulas, and as the design process progresses, a more detailed calculation is made with load analysis tables.

Empirical formulae can be used successfully to obtain a first estimate of the electric power demand in the pre-design stage, if the formulae are based on a sufficient number of ships with the same mission statement and comparable size. However, for the detailed design of ship and electrical systems one of the other methods is indispensable to get a more reliable result.

When empirical formulas are at hand, they can be used to determine the electric power demand or installed electric power by using, for instance, the main dimensions of the ship such as size (deadweight) or installed propulsion power. As a rule of thumb, the electric load when manoeuvring is 130 % of the electric load at sea, and the load in port (no loading or discharging) is 30 to 40 % .[8]

This full electrical load analysis is a detailed tabulation of the total connected load and the operating loads at sea, during maneuvering and in port. Operating loads are determined by applying a service factor to the expected connected load for each application for each operating condition. The service factor assigned to each application is a combined load factor and diversity factor representing the percent of its own possible maximum that is contributed to the load on the generator over a 24 hour period. Occasional loads such as fire pumps, anchor windlass, etc is assumed to have zero factor. The aggregate generating capacity, exclusive of any emergency will always be greater than the peak load determined by the analysis. The probability of installing additional loads in the future should also be considered when determining the aggregate generator capacity. [1] A typical load analysis is shown in Appendix 7.

An alternate approach uses a load factor and simultaneity factor rather than just the single service multiplier. This table is shown in Attachment D2. The load factor indicates the relative (%) load of the machinery and thus specifies how much electric power is absorbed in an actual situation. A steering gear pump for example will only occasionally be fully loaded. The load factor, which varies between 0 and 1, accounts for this. A typical load factor for a steering gear pump is 0. 1.

The simultaneity factor accounts for pieces of machinery that are not operated continuously but intermittently. Examples of these are air compressors, fuel pumps and ballast pumps. The simultaneity factor indicates the relative (%) mean operational time of the machinery. This factor also varies between 0 and 1. It is often possible to make a good estimation of this factor by comparing the machine capacity and the average capacity demand. As described above in many cases no distinction is made between the load factor and the simultaneity factor, and the two factors are combined into one service factor. This does, however, not provide a clear insight into the actual load demand.

The column *average absorbed power is* the product of the absorbed power, the number in service, the load factor and the simultaneity factor. The total of this column indicates the total absorbed power for the given operational condition. The estimation of the load and simultaneity factors is the most difficult part of the electric load analysis. These factors are often estimated too high, in order to minimise the risk of designing a plant with a generator capacity that is too small. This results in an overestimation of the electric power demand, and consequently the chosen generator capacity is too large. Disadvantages are obvious:

- high investment
- low average load of the diesel generator sets, leading to specific fuel consumption that is not optimal and internal pollution of the engine.

A thorough study of similar ships should form the basis for load and simultaneity factor estimates.

A more accurate electric power demand estimate can be achieved with a simulation of ship's operations under the various operational conditions. This method requires a considerable insight into the ship's operations. A simulation takes interactions between pieces of equipment into account and can model load and simultaneity factors by using stochastic probability distributions. In particular the use of probability distributions can make the method more accurate than an ordinary electric load balance.

The advantage of the stochastic probability distribution is explained with an example: the steering gear pump. The load factor was introduced in the preceding paragraph. The steering gear pump is only occasionally fully loaded; the load factor accounts for this by implying that it is partially loaded all the time. With a probability distribution the load of the pump can be modelled to be zero or full-load. After sufficiently long simulation the distribution provides insight into the expected minimum and maximum loads and the chances of exceeding a certain maximum. With this it is possible to make a well-founded choice concerning the number and capacity of the generators and transformers [8]

Short Circuit Calculations and Discrimination of Protective Devices.

The installation of large capacity electrical systems has resulted in the increase in magnitude of possible short-circuit currents throughout the electrical distribution system. To maintain continuity of electrical service, with the least possible interruption from fault currents, it is necessary to provide adequately rated circuit protective devices that are properly coordinated with each other throughout the distribution system. These protective devices are usually circuit breakers; however, fuses may be used for many applications.

To determine the proper selection and application of circuit protective devices, a fault current analysis of the entire electrical generating and distribution system, should be made. In calculating the total magnitude of fault currents, it is necessary to determine not only the contribution of short-circuit current from the generators, but also the contribution from motors connected to the system. The contribution from induction motors decays very rapidly; however, the time of decay usually spans the time range of circuit breaker operation and should be considered.

The fault-current analysis should be based on the total number of generators, including spare units, that may be operated in parallel, the number of motors expected to be operating, and the reactance and resistance of cables and transformers in the circuit in question.

As an example, calculations for a shipboard electric plant with two 1250 kW, 450 volt. 3-phase generators operating in parallel, and an induction motor load of 1800 amps at the time of a fault and a fault occurring on the generator switchboard main bus, gives a current available at the switchboard main bus of 24,673 amps. This value is the minimum interrupting rating for the circuit protective devices installed on the generator switchboard.

Appendix 7 also contains calculations for maximum fault currents at different points of a ship's distribution system.

The fault current analysis should be extended to include calculations of minimum fault currents for remote points of the system to determine that a sufficient current is available to ensure the proper tripping of each protective device. Using the fault current analysis as a basis for the selection of protective devices, a sequence of circuit-breaker tripping can be determined that will isolate any fault in the distribution system with a minimum interruption of power to other services. In the event of a fault, the nearest protective device on the supply side of the fault should open to isolate the faulted circuit; other protective devices on the supply side of the fault should remain closed.[1]

Main & Emergency Switchboard

Drawings and schematics of layout, instrumentation etc are often required. Bus bar construction and the mechanical stresses likely to occur under short circuit conditions documentation may be needed. Also schematics of starters for essential motors and thrusters. Details of power converters, power supplies and UPS systems are also required.

Load Balance Calculations

Power consumption balance information covering operational modes: at sea; manoeuvring; special operations and emergency conditions.

Electrical Propulsion

Where electrical propulsion systems are used, additional documentation includes

- Description of operational modes

- Calculations of propulsion motor start up times
- Power management
- Electrical propulsion motor details.

CLASSIFICATION SOCIETY DOCUMENTATION

Appendix 8 contains the general provisions for electrical installations on high speed craft issued by Germanischer Lloyd. The complete set of design documents to be submitted is shown on page 12-1.

Appendix 9 contains an extract from the specific requirements necessary for initial planning and basic design of electrical systems on drilling units issued by ABS.

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