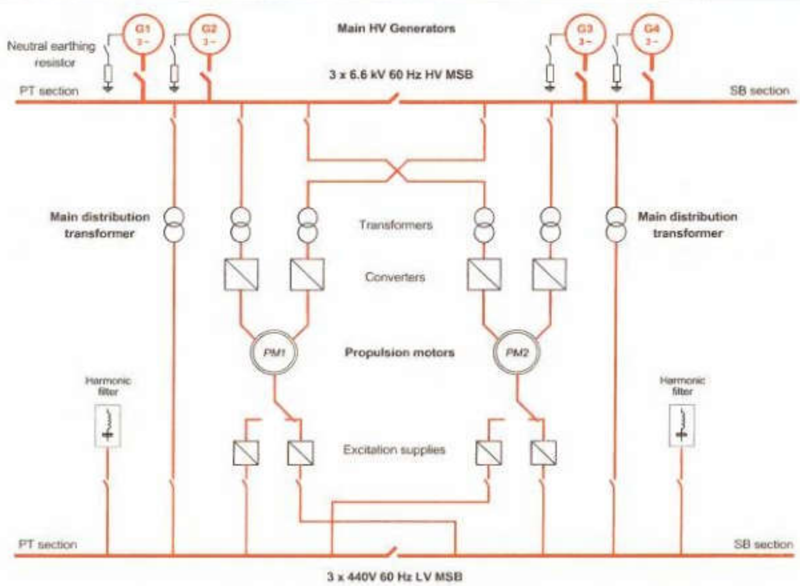
PRACTICAL MARINE ELECTRICAL KNOWLEDGE

Third Edition



Dennis T. Hall BA (Hons), CEng MIEE, MIMarE

WITHERBY **Seamanship** INTERNATIONAL

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Preface

This book's objective is to help marine and electrical engineers acquire the knowledge required by STCW for management and operational level endorsements and to become more familiar with various electrical applications that can be found on board ship.

The systems are explained in terms of their operating principles and safe working practice. The type and significance of various electrical appliances, circuits and faults are considered and a common troubleshooting practice is examined.

A wide range of onboard ancillary electrical services are described, along with detailed information on battery support, care and maintenance.

The application and operating principles of electrical propulsion are examined, as well as high voltage practice, safety procedures and testing methods.

This book will be helpful to management and operational level marine engineers, electrical engineers and electricians, as well as students currently studying marine and electrical engineering.

About the author, Dennis Hall (1940-2009)

Dennis Hall had long experience with the marine industry, with initial training in shipbuilding followed by practical experience in the Merchant Navy as an Electrical Officer. This was followed by design and inspection work for large power industrial electrical systems around the world. Further experience and knowledge was acquired in the Royal Navy where he was introduced to the requirements and effective delivery methods for the training of engineering personnel. At South Tyneside College, as a lecturer, manager and as Head of Electrical Power Systems, he examined many ship types and visited many marine colleges in Europe, USA and Japan.

Dennis was driven to meet the training and education needs of the marine industry and this book has, for many years, been the mainstay. The technical editors of Witherby Publishing Group have been careful to ensure that the straightforward and informative style of Dennis' book has been maintained, while bringing in additional material that updates and expands the subject matter.

Contents

Chapter One
Ships' Electrical Systems, Safety and Maintenance

Auxiliary services on board ship include thrusters, cargo cranes, engine room pumps, compressors and fans, deck winches and windlasses, general lighting, catering and air conditioning. Electrical power is used to drive the majority of these auxiliary services. The electrical power system on board ship should provide a secure supply to all loads and have built-in protection for the equipment and operating personnel.

The general scheme of a ship's electrical power system, as shown in Figure 1.1, is common to nearly all ships.

The main AC generators (sometimes called alternators) produce the electrical power, which is supplied to the main switchboard and then distributed. An emergency generator and emergency switchboard maintain supplies in the event of a main power failure.

The generators may be driven by a diesel engine, by a steam or gas turbine, or by the main propulsion engine as a shaft generator. The type of prime mover is determined by the design of the ship and by economic factors.

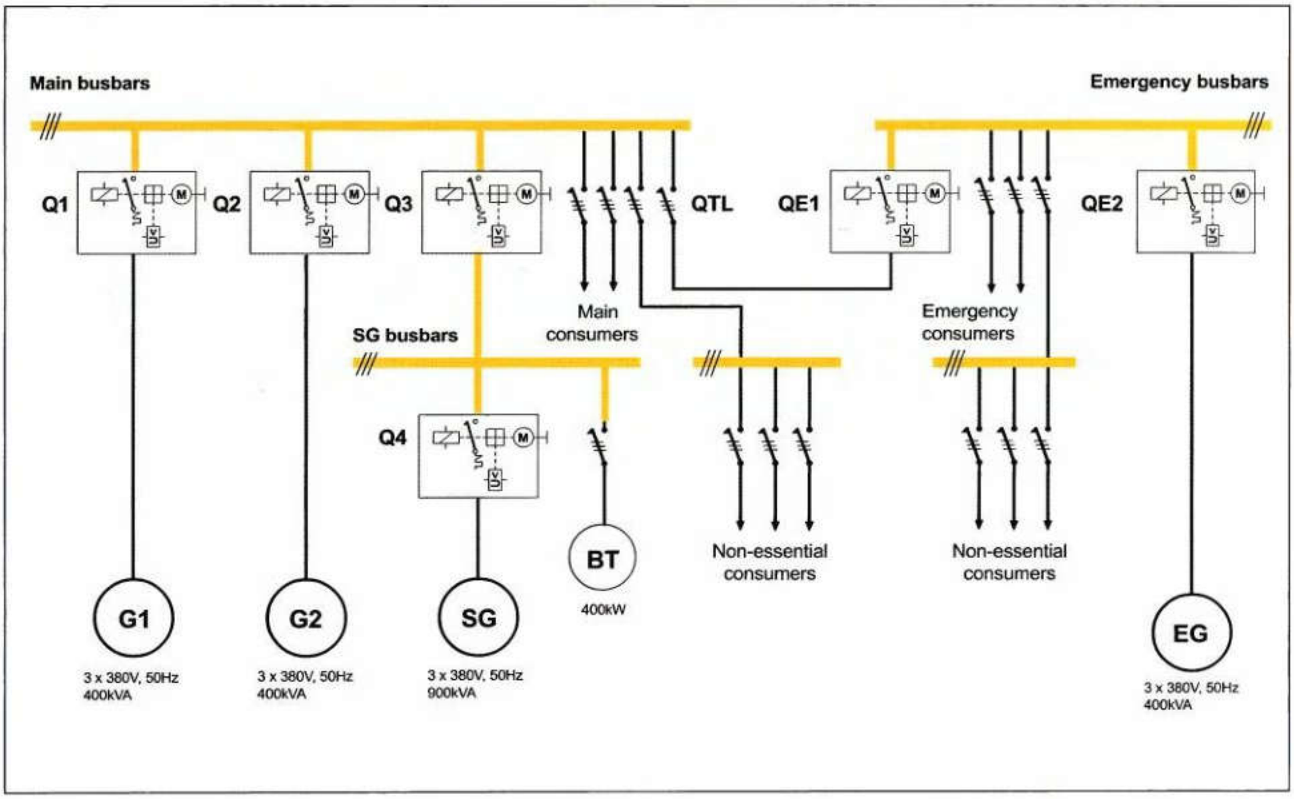


Figure 1.1 - Electrical power system

The combined power rating of the generators is determined by the overall demand from the ship's electrical load.

Large passenger ships usually have 4 large generators, rated at 10 MW or more, to supply the electric propulsion motors and the hotel services on board. A cargo ship may have two main generators, typically rated from 350 to 1000 kW, which are sufficient to supply the engine room auxiliaries while at sea and the cranes for handling cargo while in port. The limited load consumed during an emergency means that an emergency generator may be rated from about 50 kW for a small coaster to about 300 kW or more for a container ship. The shipbuilder must estimate the number and power rating of the required generators by assessing the power demand of the load for all situations, whether at sea or in port, or as required by the registering authority.

Electrical power on board ship is commonly generated at 380 V, 50 Hz (sometimes 440 V, 60 Hz). Ships with a very large electrical power demand will require generators that operate at a high voltage (3.3 kV, 6.6 kV or 11 kV) to limit the size of normal load current and the prospective fault current.

The British Standard (BS) and International Electrotechnical Commission (IEC) definition of low voltage is 50 V AC to 1000 V AC (the IEC gives this definition to harmonise British and European standards).

Lighting and other low power ancillary services usually operate at 220 V. Single-phase AC transformers are used to reduce the 380 V (440 V) system to these lower voltage levels.

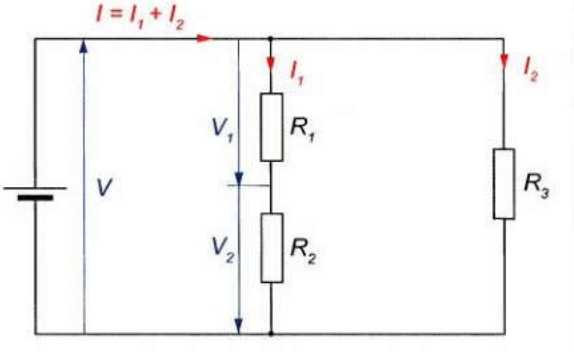
Where portable equipment is to be used in dangerous, hot and damp locations, it is advisable to operate at 48 V, or even 24 V, supplied through the use of a step-down transformer. Occasionally, transformers are also used to step-up voltages, eg to supply a large 3.3 kV bow thruster motor from a 440 V switchboard supply.

Batteries for essential services operate at 12 V or 24 V DC.

1.1 Circuit Calculations

The following is a brief revision of DC and AC circuits and calculations.

DC circuit



$$R_T = R_1 + R_2 + R_3 + \dots \textit{ (in series)}$$

$$\frac{1}{R_T} = \frac{1}{R_1} + \frac{1}{R_2} + \frac{1}{R_3} + \dots \textit{ (in parallel)}$$

$$V = I \times R \textit{ (Ohm's Law)}$$

$$\sum emfs = \sum pds \text{ (Kirchhoff)}$$

$$\sum I_{IN} = \sum I_{OUT} \text{ (Kirchhoff)}$$

$$P = V \times I = I^2 \times R$$

Example:

Using the above circuit with a 110 V DC supply and $R_1 = 6\ \Omega$, $R_2 = 5\ \Omega$, $R_3 = 5.5\ \Omega$, calculate all currents, supply power and pd across the 6 Ω resistor.

Determine as,
$I_1 = 110/(6 + 5) = \mathbf{10\ A}$ *and* $I_2 = 110/5.5 = \mathbf{20\ A}$

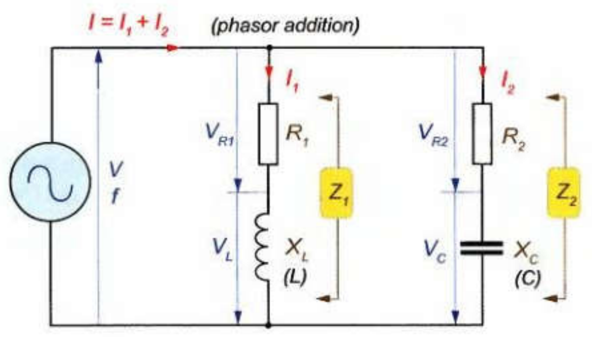
so supply current is $\mathbf{I} = \mathbf{30\ A}$

Supply power is $P = V \times I = 110 \times 30 = \mathbf{3.3\ kW}$

[check with $P = \sum(I^2R)$*]*

pd (potential difference) across 6 Ω resistor is $I_1 \times 6 = 10 \times 6 = \mathbf{60\ V}$

Single-phase AC circuit



$X_L = 2\pi fL\ (\Omega)$ $\quad$ $X_C = 1/2\pi fC\ (\Omega)$

$$Z = \sqrt{R^2 + X_L^{\ 2}} \quad \text{or} \quad Z = \sqrt{R^2 + X_C^{\ 2}}$$

$$I = V/Z$$

power factor $= \cos\varphi = R/Z = P/S$ *(lag or lead)*

$$P = V \times I \times \cos\varphi \text{ or } P = I^2R\ (W)$$

$$Q = V \times I \times \sin\varphi \text{ or } Q = I^2X\ (VAr)$$

$$S = V \times I \text{ or } S = I^2Z\ (VA)$$

Example:
Using the above circuit with a 220 V, 60 Hz AC supply and $R_1 = 6\ \Omega$, $R_2 = 5\ \Omega$, L = 0.1 H, C = 100 μF

Calculate all currents, supply power, overall power factor and pd across the 6 Ω resistor.

Determine as,

$X_L = 2 \times \pi \times f \times L = 37.7\ \Omega$ and $X_C = 1/2 \times \pi \times f \times C = 26.5\ \Omega$

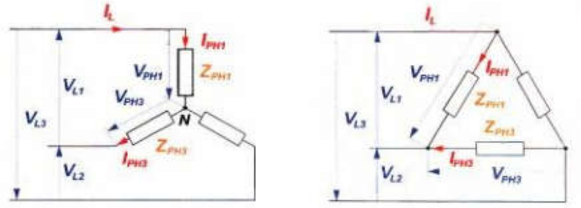
Then $Z_1 = 38.2\ \Omega$ at 81° *(lagging)*
and $Z_2 = 27\ \Omega$ at 79.3° *(leading)*
So, $I_1 = 220/38.2 =$ **5.76 A** *lagging V by 81°*
and $I_2 = 220/27 =$ **8.15 A** *leading V by 79.3°*

The total supply current is the ***phasor*** *sum of* I_1 *and* I_2 *which must be resolved into 'in-phase' (horizontal) and 'quadrature' (vertical) components before adding.*

The result (for you to check) is
$I =$ **3.34 A** *at 43.8° leading*
Supply Power is $P = 220 \times 3.34 \times \cos 43.8° =$ ***531 W***
[check with $P = \sum(I^2R)$*]*

Overall power factor is $\cos 43.8° =$ ***0.72 leading***
pd across $6\ \Omega = I_1 \times 6 = 5.76 \times 6 =$ ***34.56 V***

Three-phase AC circuit



$V_L = \sqrt{3} \times V_{PH}$ and $I_L = I_{PH}$ *(in Star)*

$V_L = V_{PH}$ and $I_L = \sqrt{3} \times I_{PH}$ *(in Delta)*

$P_{PH} = V_{PH} \times I_{PH} \times \cos\varphi = I_{PH}^{\ 2} \times R$

Balanced three-phase: $P = \sqrt{3} \times V_L \times I_L \times \cos\varphi$

Example:
Using the above circuit with a 440 V, three-phase, 60 Hz AC supply and $Z_{PH} = 10\ \Omega$ at pf = 0.8 lagging (balanced load).

Calculate phase and line currents and supply power when connected as:
(a) Star and (b) Delta

Determine as,

(a) in Star, $V_{PH} = 440/\sqrt{3} = 254\ V$

so $I_{PH} = 254/10 =$ ***25.4 A***

and $I_L = I_{PH} =$ ***25.4 A*** *also*

$P = \sqrt{3} \times 440 \times 25.4 \times 0.8 =$ ***15.49 kW***

(b) in Delta, $V_{PH} = V_L = 440\ V$

so $I_{PH} = 440/10 =$ ***44 A***

and $I_L = \sqrt{3} \times 44 =$ ***76.2 A***

$P = \sqrt{3} \times 440 \times 76.2 \times 0.8 =$ ***46.46 kW***

(notice this power is three times the value in star)

1.2 Electrical Diagrams

Symbols are used to represent the different items of equipment in a circuit. The shipbuilder will have provided a complete set of electrical diagrams and it is important that you study them to be able to read, understand and use them as an aid in locating electrical faults.

A block diagram shows, in simplified form, the main interrelationships between the major elements of the system and how the system works or may be operated. Such diagrams are often used to depict control systems and other complex relationships. The block diagram in Figure 1.2 describes the main functions of an overcurrent relay (OCR) used to protect the motor starter. Its circuit diagram shows one way of realising the overall OCR function. Diagrams like this state the function of each block, but usually do not give any information about the components in each or how they are interconnected.

A power diagram, as shown in Figure 1.3, represents the main features of a system and its bounds. Its main use is to illustrate the ways of operating the system. Details are omitted to make the diagram as clear as possible.

A circuit diagram, such as Figure 1.4, shows the detailed functioning of a circuit. Graphical symbols are arranged to show the operation as clearly as possible, without regard to their actual physical layout. The coil and its related contacts are identified by a number and letter code. Although there are international standards (IEC, EN, NEMA, etc) for the symbols that represent electrical components, you must be prepared to meet various different symbols representing the same component depending on the standard followed by the equipment's manufacturer.

The use of a circuit diagram enables personnel to understand the circuit and to follow each sequence in the operation from the moment of turning on the power supply and initiating the operation (eg by pressing a start button) to the final act (eg starting of the motor). If the equipment fails, the engineer can follow the sequence until he comes to the operation that has failed. The components involved in that faulty operation can then be examined to locate the suspect item. There is no need to examine other components that are known to function correctly and have no influence on the fault, so the work is simplified. A circuit diagram is an essential tool for fault finding.

A wiring diagram shows the components in the approximate positions they occupy within the actual enclosure. The components are shown complete and are simply represented by a block, with the necessary terminals clearly marked with reference numbers. A different thickness of line can be used

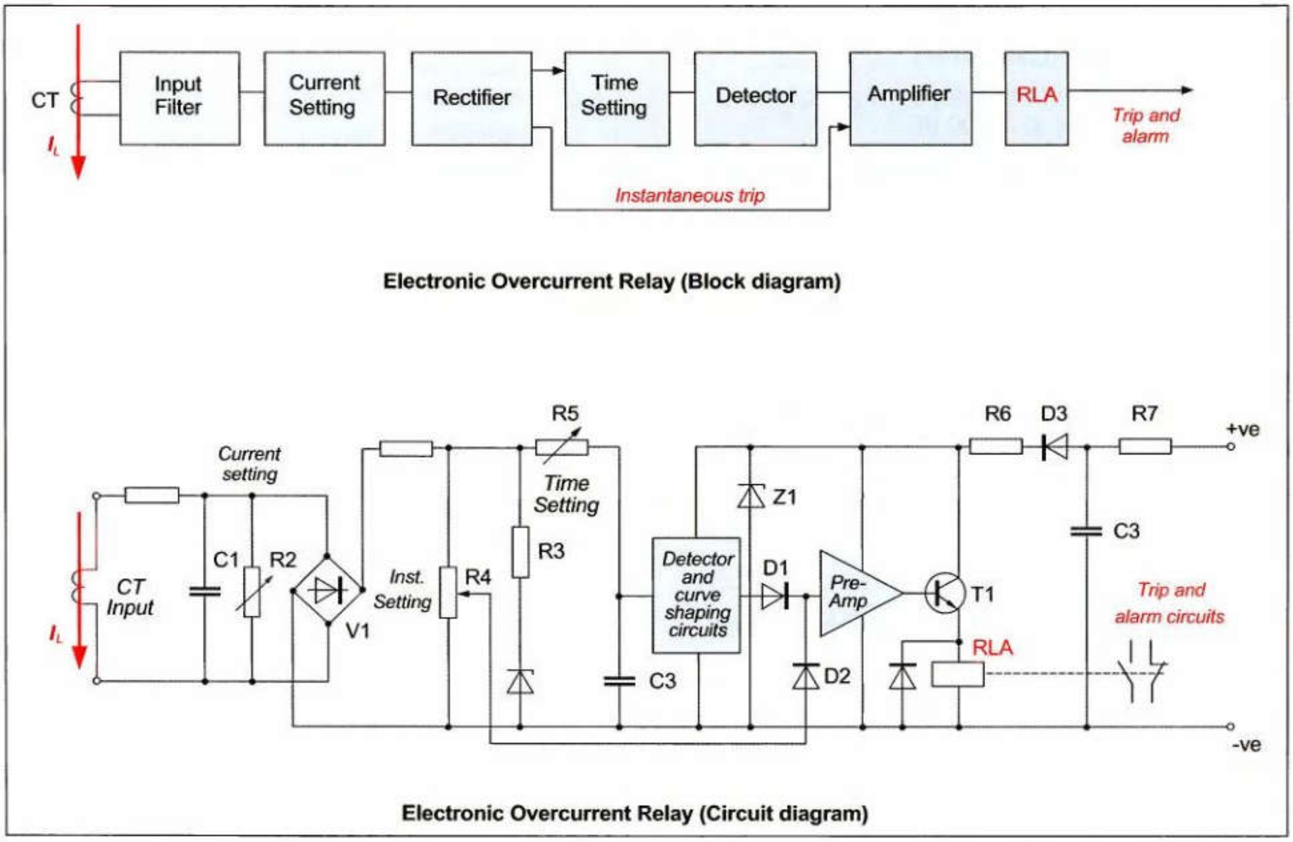


Figure 1.2 - Block and circuit diagrams

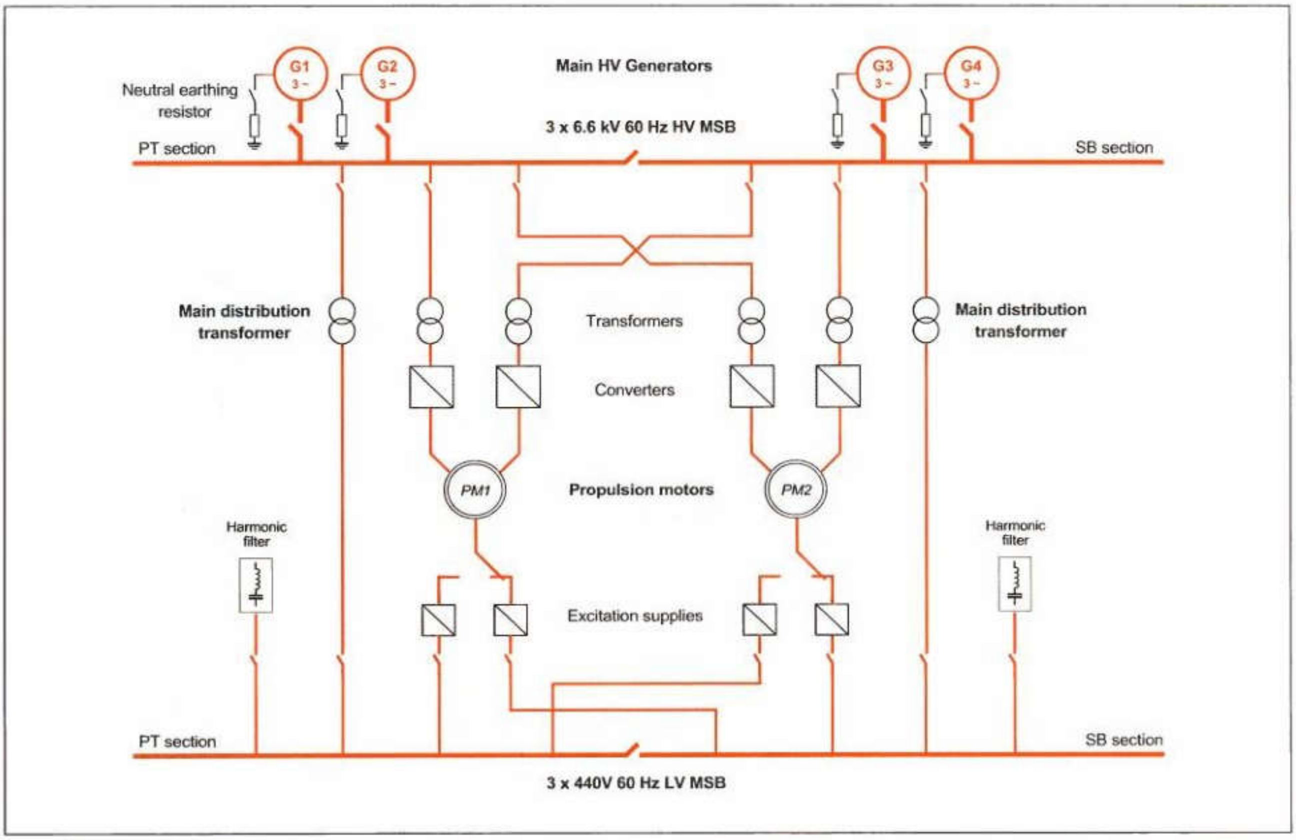


Figure 1.3 - Power system diagram

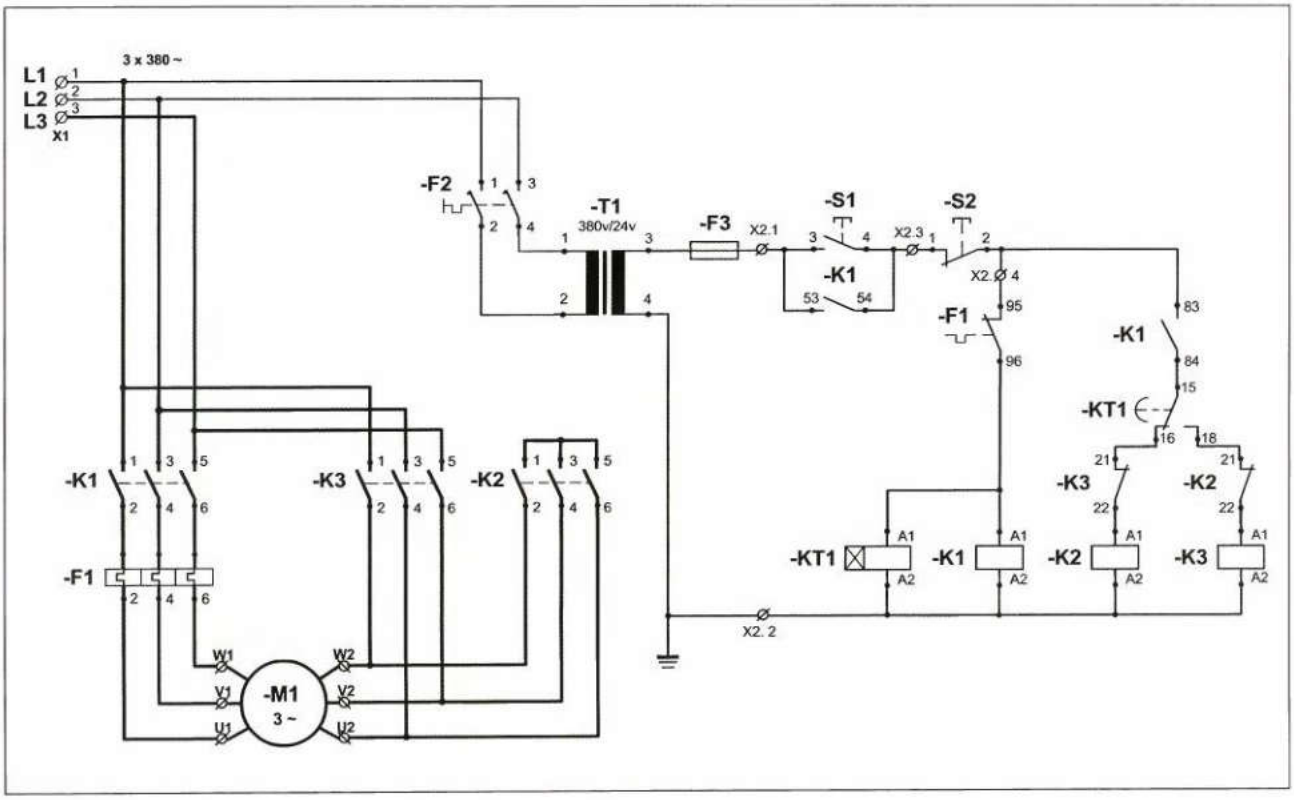


Figure 1.4 - Star-Delta motor starter (power and control diagram)

to differentiate between power and control circuit connections. The wiring diagram in Figure 1.5 is of the same starter shown in Figure 1.4.

A wiring diagram may be of a fairly simple circuit, but its layout makes it quite difficult to use and to understand the sequential operation of the circuit. The main purpose of a wiring diagram is to instruct the wiring installer how to construct and connect the equipment. It is of little use in troubleshooting other than for identifying the exact position of suspect components, terminals and wires.

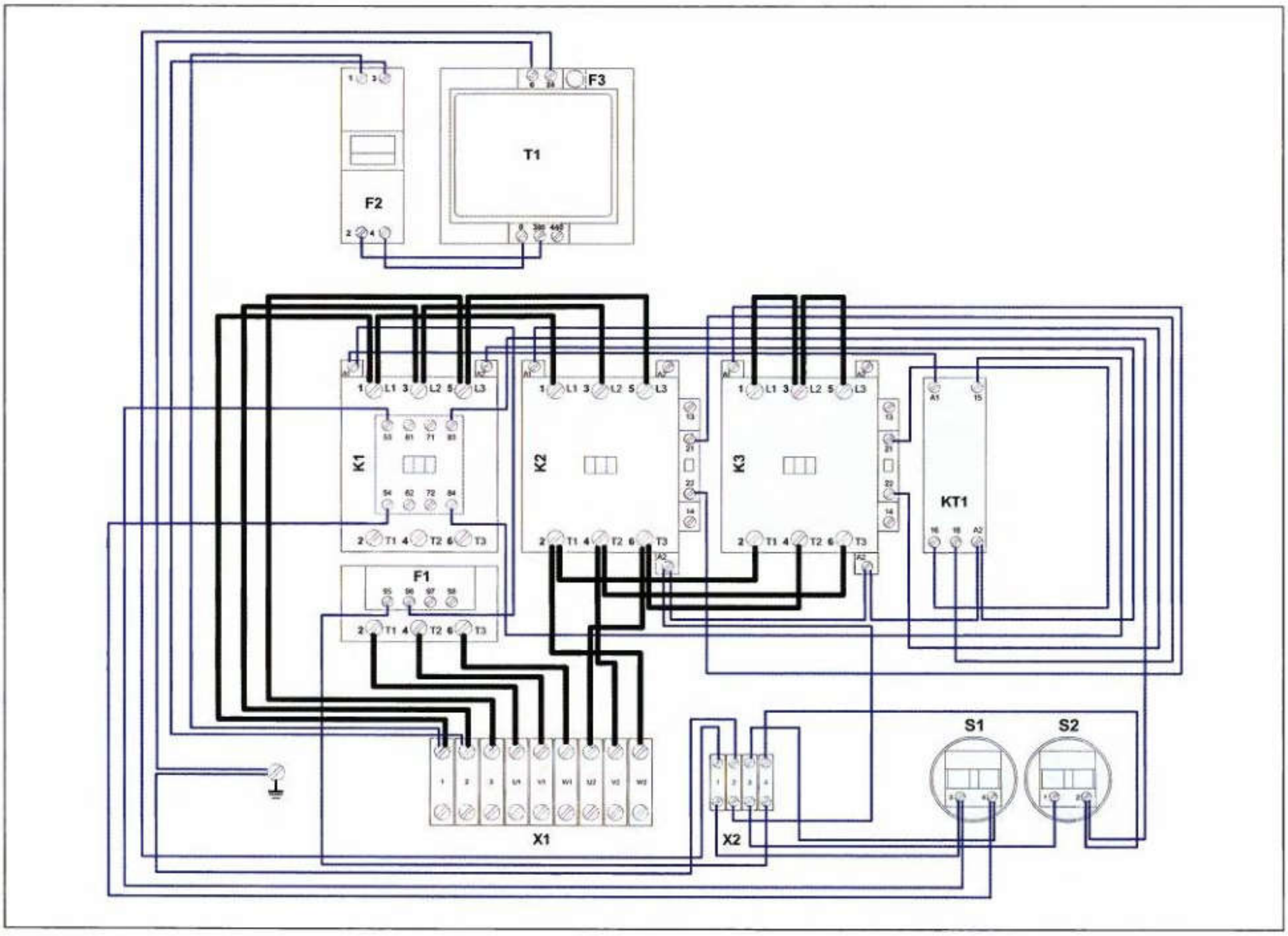


Figure 1.5 - Star-Delta motor starter wiring diagram

QUESTION

What should be done if difficulties arise in locating a fault on an item of equipment and only a wiring diagram is available?

ANSWER

It may well save time and trouble to convert the wiring diagram into a circuit diagram. When converting a wiring diagram into a circuit diagram, certain basic rules and conventions should be followed:

- Every sequence should be drawn from left to right and from top to bottom (where possible)
- each stage should be in order of occurrence from left to right
- all contacts and components that are in series should be drawn in a straight line (where possible) with the component they control (eg contactor's coil) located at the bottom of the diagram
- all contacts and components that are in parallel should be drawn side by side and at the same level to emphasise their parallel function
- all major components operating at busbar voltage should be drawn at the same level (or aligned horizontally) to help identify the required components quickly
- all contacts should be shown either open or closed, ie their 'normal' or de-energised condition.

There are other diagrammatic conventions, but block, system, circuit and wiring diagrams are the main types in general use for electrical work. Other types are sometimes used to provide information where the basic types are unsuitable (eg a pictorial view of a component).

Diagrams should be regarded as an essential tool when carrying out work on electrical equipment.

1.3 Electrical Safety

Very high values of voltage, current, power, temperature, force, pressure, etc create the possibility of danger in an engineering system. To minimise the safety risk to personnel and equipment, systems must be designed and manufactured to comply with international standards and be correctly installed. Before attempting any electrical work, there are some basic safety precautions to be taken.

Regulations control the construction, installation, operation and maintenance of electrical equipment so that danger is eliminated as far as possible. Minimum acceptable standards of safety are issued by various bodies, including national governments, international governmental conventions (eg SOLAS), national and international standards associations (eg BS and IEC), industry societies (eg IEE), Classification Societies (eg Lloyd's Register), etc.

Ships' staff must operate equipment in a safe manner and maintain it in a safe condition at all times. Failure to do so will cause danger, with potentially serious consequences. Keep in mind an essential list of DOs and DO NOTs when working with electrical equipment:

- ✓ DO get to know the ship's electrical system and equipment. Study the ship's diagrams to pinpoint the location of switches, protection devices and interlocks supplying distribution boards and essential items of equipment. Write down this information in a notebook. Become familiar with the normal indications on switchboard instruments so that abnormal operation can be quickly detected.
- ✓ DO operate equipment according to the manufacturer's recommendations.
- ✓ DO maintain equipment according to the manufacturer's recommendations or the shipowner's maintenance procedures.
- ✓ DO ensure that all guards, covers and doors are securely fitted and that all bolts and fixings are in place and tight.
- ✓ DO inform the duty engineer and OOW before shutting down essential equipment for maintenance.
- ✓ DO switch off and lock-off supplies, remove fuses and display warning notices before removing equipment covers.
- ✓ DO confirm that circuits are DEAD (by using an approved voltage tester) before touching conductors and terminals.
- ✗ DO NOT touch live conductors for any reason or under any circumstance.
- ✗ DO NOT touch rotating parts.
- ✗ DO NOT leave live conductors or rotating parts exposed.
- ✗ DO NOT overload equipment.
- ✗ DO NOT neglect or abuse operating and overhauling procedures.

You should think SAFETY at all times and develop a safety conscious attitude. This may well save your life and the lives of others. Most accidents occur due to a momentary loss of concentration or attempts to violate safety procedures and safe working practices implemented by the company.

1.4 Electric Shock

Many people have experienced an electric shock at some time and, while it is generally just an unpleasant experience, at its worst it can be fatal.

Anyone who has access to live electrical equipment must be fully aware of first aid and safety procedures related to electric shock. Copies of electrical safety information should be displayed throughout the ship.

Electric shock is caused by the flow of current through your body. This is often from hand to hand or from hand to foot. A shock current as low as 15 mA (AC or DC) may be fatal.

Figure 1.6 - Electrical safety warning

The size of shock current is related to the applied voltage and your body resistance. Unfortunately, your body resistance goes down as the applied voltage goes up. This means that the shock current is further increased at high voltages. The size of your body resistance also depends on factors such as your state of health, the degree of contact with live wires and the perspiration or dampness on your skin. Typical dry full-contact body resistance is about 5000 Ω at 25 V, falling to about 2000 Ω at 250 V.

QUESTION

What would the equivalent shock current levels be at 25 V and 250 V?

ANSWER

5 mA and 125 mA.

Voltages of about 48 V and below are regarded as reasonably safe for portable hand tools. This is why special step-down isolating transformers are used with portable tools and handlamps. These transformers supply the tool or lamp at 48 or 24 V AC but, because the secondary winding is centre-tapped to earth, the maximum shock voltage to earth is 24 or 12 V AC.

Electric shock is often accompanied by falling, which may cause additional physical injury and require first aid. If the shock victim is unconscious, resuscitation must take priority over other first aid. Resuscitation techniques are mandatory on first aid training courses.

1.5 Insulation Resistance

All electrical equipment has insulation. The purpose of the insulation is to prevent direct contact with live conductors. The value of the insulation resistance must be high enough to prevent current leaking away from conductors. Insulation resistance is measured between:

- Conductors and earth
- conductors.

The minimum acceptable value of insulation resistance is limited by the relevant register regulations.

The flow of leakage currents through surface deposits is called tracking, which is also affected by the creepage and clearance distances between terminals, as shown in Figure 1.7. Equipment must be maintained in a clean condition to prevent tracking and to maintain the value of insulation resistance above the minimum acceptable value (usually at least 1 MΩ for voltages up to 1000 V).

Insulation materials are non-metallic. Insulation is adversely affected by many factors, such as humidity, temperature, electrical and mechanical stress, vibration, chemicals, oil, dirt and old age.

Traditional insulation materials include cotton, silk and paper. They may be either dry or treated with insulation varnishes or resin compounds to exclude moisture and other harmful substances. Other materials include ceramic, mica, glass fibre, PVC and other types of plastics and compounds. An extensively used medium not normally considered as an insulation material is the air surrounding the electrical components.

The majority of insulation materials in common use cannot withstand temperatures that are much in excess of 100°C.

All electrical equipment heats up when carrying load current, with a consequent rise in temperature. This temperature rise will be above that of the ambient cooling air temperature.

All marine electrical equipment is constructed and rated to work satisfactorily in a maximum ambient air temperature of 45°C. Under these conditions the expected temperature rise will not exceed the permitted temperature limit set for the insulation material. It is, therefore, the insulation material that dictates the maximum permitted operating temperature of the electrical equipment.

There are exceptions, such as oil circulating pumps for thermal oil plants, that operate at a far higher temperature. Therefore, this insulation must be rated for safe working in such an environment.

Insulation is classified according to the maximum permissible temperature at which it is safe to operate the electrical motors. It is officially called *Insulation Class* and it is often abbreviated on the nameplates of motors as *'Ins. Cl.'*. Classes of insulation are listed in IEC and NEMA standards. Classes O, A, B and C were in general use for many years, but class O is now known as Y and some classes (E, F and H) were added to legislate for new material and processes in this field.

The maximum temperature allowed for each of these classes is:

Insulation Class	Y	A	E*	B	F	H
Temperature	80°C	105°C	120°C	130°C	155°C	180°C

(*) Insulation Class E is used by European manufacturers for marine applications.

These are steady surface temperatures measured with equipment stopped and no flow of cooling air. When considering a suitable operating temperature for the electric motor, the temperature in the hottest point of the winding must also be taken into consideration, referred to as the *hot spot* temperature. For example, the hot spot in a coil will be near the centre of the winding. From that point, there is temperature gradient to the surface of the stator core meaning that the temperature is not uniform throughout the coil. The only practical means available to determine the temperature, therefore, is either by measuring the change in resistance of the winding or the surface temperature by thermometer.

A continuously rated motor will eventually reach a steady temperature at which the heat in the windings and magnetised cores and the heat arising from frictional losses will be dissipated at the same rate as they are generated. The difference between this steady temperature and that of the incoming cooling air is the temperature rise. For all practical purposes, this rise is always the same, regardless of the temperature of the cooling air.

For example:

If a motor is tested in an ambient temperature or cooling air temperature of 20°C, and a motor temperature of 55°C is recorded, the rise is 35°C. When the same motor is at an ambient temperature of 45°C, the rise will still be 35°C, giving a total motor temperature of 80°C.

Having determined the appropriate hot spot temperature for a given class of insulations and, from that, the surface temperature, the permissible temperature rise is reached by deducting the maximum ambient temperature under which the machine will be required to operate.

A motor operating continuously with these hot spot temperatures would have an expected life of 15 to 20 years before the insulation failed. However, that life expectancy would be halved for every 10°C over the permissible temperatures.

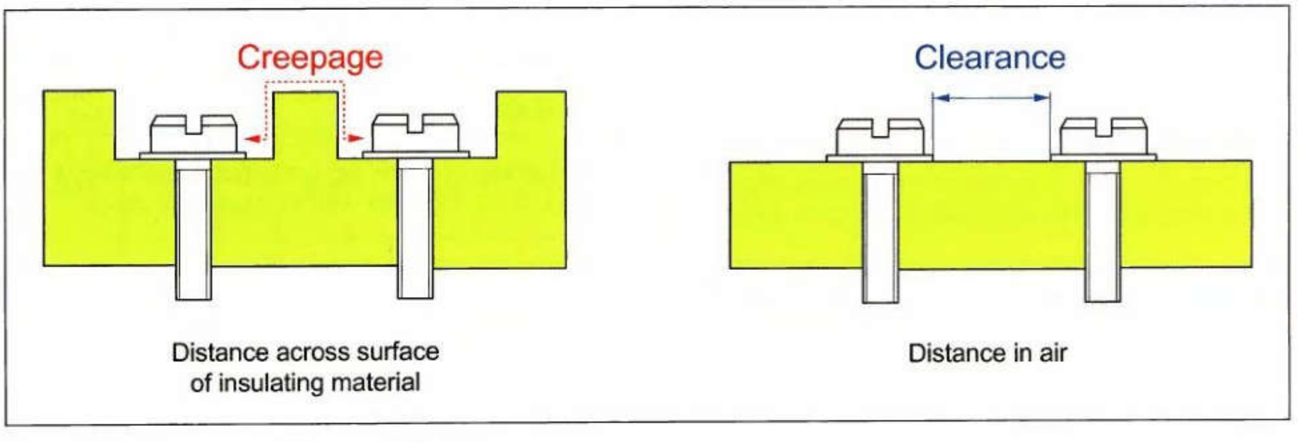


Figure 1.7 - Creepage and clearance distances

1.6 Circuit Testing

This section looks at the electrical circuit testing operations you may need to carry out and the instruments you will need to do so.

The main tests are for:

Insulation Resistance (IR)	Using a (megger) tester (at 500 V DC for a 440 V circuit) Do not use a multimeter for this task
Continuity Resistance (Low Ω)	Typically using a multimeter
Component Resistance (Ω or kΩ)	
Voltage (AC or DC)	
Current	Using a clampmeter (or multimeter for small currents)

Figure 1.8a - Insulation resistance (IR) tester

Figure 1.8b - 'Fluke' electronic insulation tester

1.7 Insulation Testing

A measurement of the insulation resistance (IR) provides one of the best guides to the state of health of electrical equipment. The resistance should be measured between insulated conductors and earth, and between conductors.

An insulation tester is a high reading resistance meter using a high test voltage – usually 500 V DC. The test voltage is produced either by an inbuilt tester in a hand-driven generator (as illustrated in Figure 1.8a) or by an electronic insulation tester (Figure 1.8b). A test voltage of 500 V DC is suitable for testing ships' equipment rated at 440 V AC. Test voltages of 1000 V and 5000 V are used for high voltage (HV) systems on board ship.

Before applying the test, the equipment to be tested must be disconnected from the live power supply and locked-off according to standard safety procedures.

To prove the basic operation of the tester, short the two probes together and rotate the rocker switch (or press the 'test' button on the electronic-type instrument). The pointer should indicate 0Ω.

For an IR test on a three-phase machine, measure and log the phase-to-phase insulation resistance values. Three readings should be measured as U-V, V-W, W-U, as shown in Figure 1.9.

Measure and log the phase to earth insulation resistance values. Three readings should be measured as U-E, V-E and W-E.

Note: Insulation resistance decreases as temperature increases.

An example of an IR log for a motor is shown in Figure 1.10, together with its graphical trend.

QUESTION

Why should the measurement of the insulation resistance of a machine be made while the machine is hot?

ANSWER

Insulation becomes more leaky (its IR value falls) at high temperatures, so testing while hot shows the realistic IR value at, or near, its working temperature. Insulation resistance can vary considerably with changing atmospheric conditions. A single reading gives little information. However, regular recording of test results may show a downward trend, which indicates impending trouble that can be remedied by preventive maintenance.

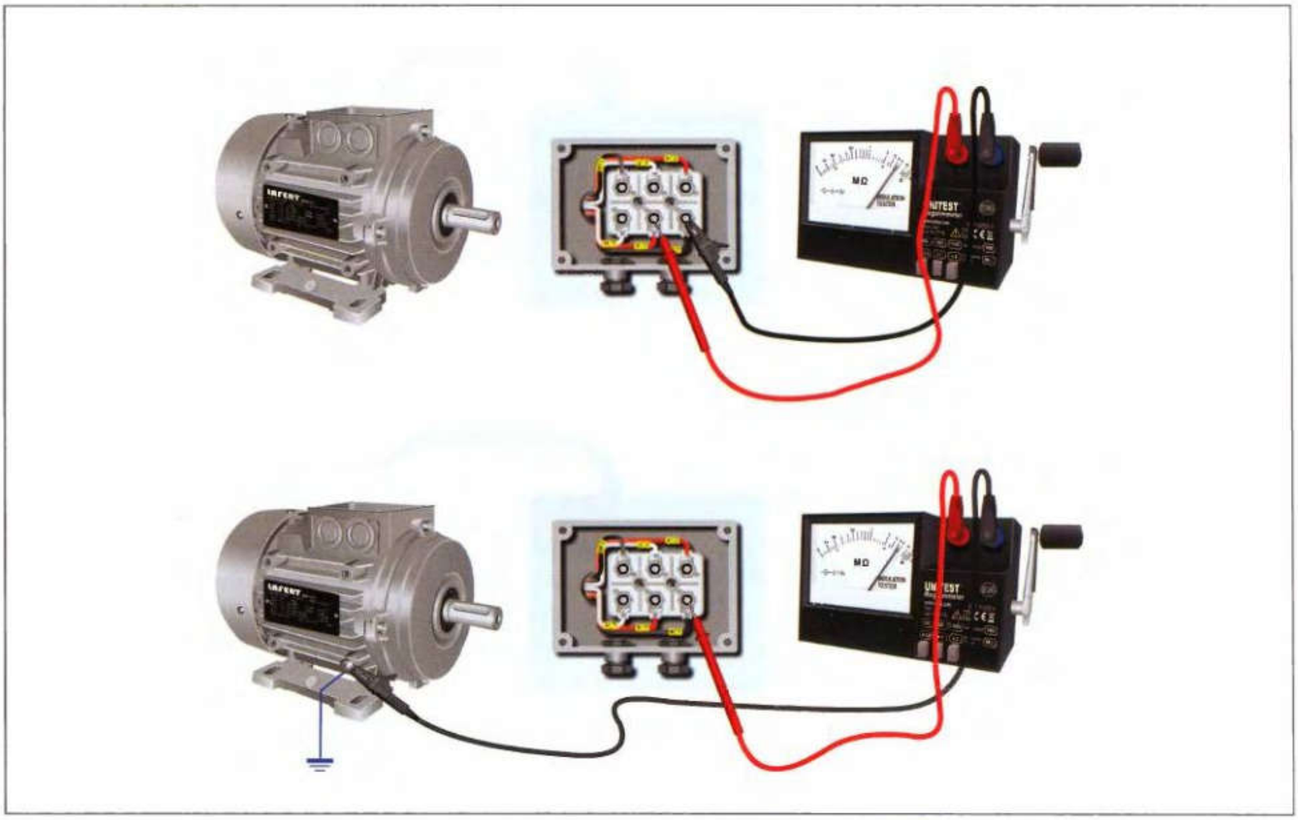


Figure 1.9 - IR test connections

AC Compressor Motor No. 1

Date	IR (MΩ)	Comments
5 Jan	*17*	*ER cold (dry-dock)*
8 Mar	*12*	*Warm*
19 Jun	*5*	*Hot and humid*
12 Sep	*2*	*Warm, cleaned & dried*
13 Dec	*25*	*Repeat test*

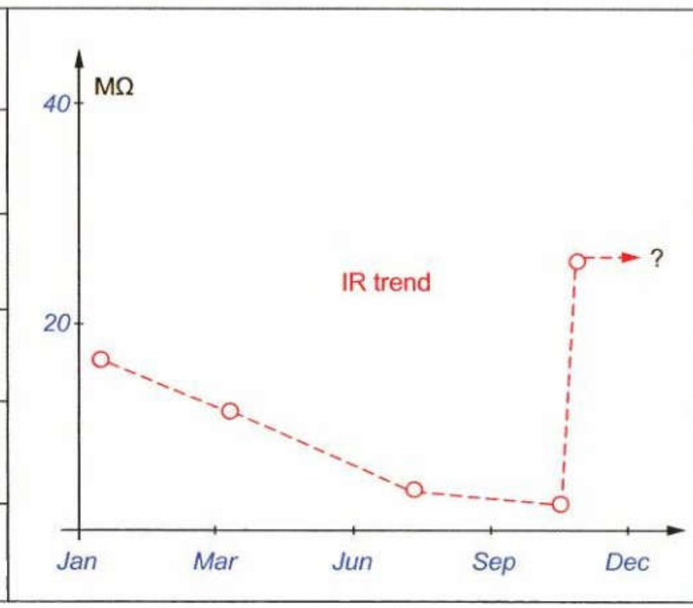


Figure 1.10 - IR log and trend

1.8 Continuity Testing

An insulation tester normally incorporates a low voltage continuity test facility. This is a low resistance instrument for measuring the continuity (or otherwise) of conductors. It can be used to measure the low resistance of cables, motor windings, transformer windings, earthing straps, etc. The procedure for use is similar to that for the insulation tester.

- ✓ PROVE the correct operation of the instrument.
- ✓ ISOLATE and lock off the equipment to be tested.
- ✓ PROVE the equipment to be dead.
- ✓ SWITCH the instrument to 'Ω' or 'continuity'.
- ✓ CONNECT the probes to the circuit.
- ✓ OPERATE the test switch and check the indication on the Ω scale. Log all readings.

In the case of three-phase motors and transformers, the comparison between readings is usually more important than the absolute value of the readings. All readings should be identical. If one reading is significantly smaller than the others it could indicate the possibility of short-circuited turns or coils in that winding. Conversely, a high continuity resistance value indicates a high resistance fault or an open circuit (eg a loose connection).

Modern types of electronic insulation testers also provide facilities to measure resistance in the kΩ range and AC voltage (acV).

1.9 Multimeters

Routine electrical test work involves measuring current, voltage and resistance, ie amps, volts and ohms. This is most conveniently carried out using a digital multimeter with auto ranging for electronic instruments.

Despite the prevalence of digital technology, analogue multimeters are still in use. However, the focus in this book will be on the use of digital multimeters.

In all instrument models, an internal battery is fitted for use when measuring resistance.

Before measuring the resistance of a component, it is essential that the circuit is switched off, locked off, and any capacitors discharged. The instrument is otherwise likely to be damaged.

Figure 1.12 - Digital multimeter

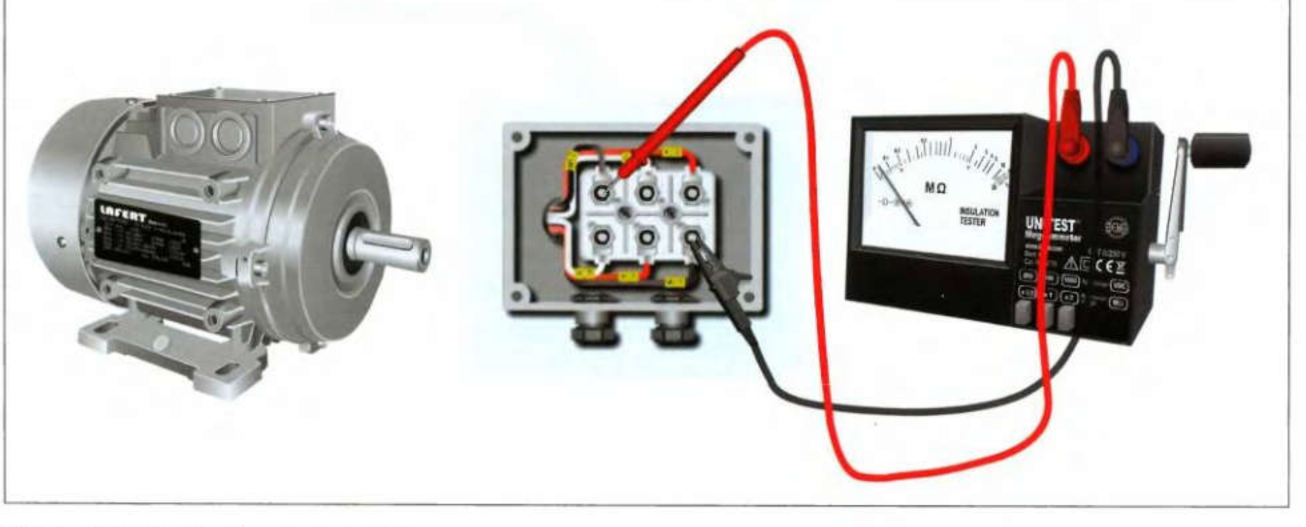


Figure 1.11 - Continuity test connections

The multimeter should be proved for correct operation before use. The manufacturer's instructions should be carefully followed for this, but a general procedure follows.

Very special care is necessary when using a multimeter to check for a live voltage. If the multimeter has been accidentally set to the current or resistance range, the instrument acts as a low resistance across the live supply. The resulting short-circuit current may easily cause the meter to explode, with local fire damage and serious consequences for the operator.

Fused probe leads are, therefore, highly recommended for use with a multimeter.

- Switch on and connect the two probe tips together. Set selector switches to 'dcV' (highest range). Display should indicate zero (000)
- repeat for all dcV selector switch positions and note the shift of the decimal point. Separate the probe tips. Set selector switches to Ω (highest range).

Display should indicate 0L (over-range) or 100 (depending upon model). Connect probe tips together – display should indicate zero (000).

- Repeat for all Ω selector switch positions and note movement of the decimal point.

Set selector switches to acV (highest range). Connect probes to a suitable known live supply. Display should indicate correct voltage.

- Test the DC voltage range also and note the polarity indication on the meter.

Instrument battery failure is usually indicated by the numeric display. The display may include 'BT' or the decimal-point may blink, or some other display effect may be used.

To preserve battery life, the majority of digital multimeters switch to standby mode automatically if not used for a time.

It is recommended that these proving tests are performed every time the instrument is used.

It is very dangerous to touch conductors believing them to be dead, which is possible if they have been checked with a faulty instrument.

To measure resistance

✓ PROVE the correct operation of the instrument.

✓ ISOLATE and lock off the equipment to be tested.

✓ PROVE the equipment to be dead.

✓ SWITCH the instrument to the appropriate resistance range, connect the probes to the equipment and note the resistance value.

✓ DISCONNECT the probes and switch the instrument to OFF.

To measure voltage

✓ PROVE the correct instrument operation.

✓ SWITCH the instrument to the highest voltage range (either acV or dcV as appropriate).

✓ CONNECT the probes to the terminals being tested. Take great care not to touch the probe tips and remember that the equipment being tested is LIVE.

✓ NOTE the voltage reading.

If a lower voltage range would give a more accurate reading, adjust the selector switches to shift the decimal point. However, most digital meters have an auto-ranging facility.

No harm will be caused to the instrument by operating the selector range switches while still connected to a live supply. However, great care must be taken not to switch into either the current or resistance mode. This would almost certainly operate the instrument overload device and may cause severe damage to the instrument and danger to yourself. Take time to operate the selector switches during the operation and think about what you are doing. Fused probe leads (as shown in Figure 1.12) are highly recommended.

✓ DISCONNECT the probes and turn off the instrument.

To measure current

Most multimeters can only measure current up to 10 A maximum. The current measuring facility is intended only for small current components and, in particular, for electronic circuits. The instrument will almost certainly be damaged if it is used to measure the current to motors and other power circuits.

The basic current range can be extended by using external shunts (DC) and current transformers (AC). These accessories are generally purchased separately from the instrument manufacturers.

The procedure to be used to measure current in a small current circuit is:

- ✓ PROVE the correct instrument operation.
- ✓ SWITCH the instrument to the highest current range (either acA or dcA as appropriate).
- ✓ TURN OFF the power to the circuit to be tested and discharge all capacitors.
- ✓ OPEN the circuit in which current is to be measured – removing a fuse-link often gives a convenient point for current measurement.
- ✓ ADJUST the test leads as designated for current measurement.

Securely connect the probes in series with the load in which current is to be measured.

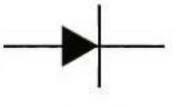
Turn ON the power to the circuit being tested. Note the current size on the meter display.

Turn OFF the power to the circuit being tested and discharge all capacitors.

Disconnect the test probes and switch the instrument to OFF. Reconnect the circuit that was being tested.

Often, the most convenient way to measure current is to use a clampmeter, which is simply clamped around an insulated conductor.

1.10 Diode Tests



Electronic diodes, and other semiconductor devices with p-n junctions, (eg the base-emitter of a transistor) can be tested using the following procedure:

- ✓ PROVE the correct instrument operation.
- ✓ SWITCH the instrument to diode test.

  If the diode is still in circuit, turn off the power to the circuit, discharge all capacitors and remove fuses.

  In this test the instrument drives a small DC current (a few mA) through the diode/p-n junction while it also acts as a voltmeter to measure the volt drop across it.

- ✓ CONNECT the two probes across the diode.
- ✓ READ the forward volt drop across the diode. This should be between 500 mV and 900 mV (0.5-0.8 V) for a healthy silicon diode or p-n junction.
- ✓ REVERSE the probe connections and the display should indicate over range.

  If the display indicates over range in both directions, the diode is open-circuit faulted. If the display indicates less than 1 V in both directions, the diode may be short-circuit faulted.

  The associated diode circuitry may be giving false readings, so the diode must be disconnected from the circuit and retested.

1.11 Current Clampmeters

Power currents (AC) can be measured simply by using a clampmeter that acts as a current transformer. The instrument's tongs are clipped round a single insulated conductor and the circuit is not interrupted.

The value of current is obtained from the magnetic flux strength around the conductor and is displayed on a digital display.

Direct current (DC) measurement is also available with clampmeters that have a flux-voltage transducer, known as a 'Hall-effect' device.

Many modern clampmeters are virtually multimeters, with the addition of facilities to measure voltage and resistance and currents up to 1000 A.

Figure 1.13 - Current clampmeter

Care must be taken when measuring the current in uninsulated conductors.

More advanced clamp type meters can indicate power and power factor in single and three-phase AC circuits by using additional connections to measure voltage.

QUESTION

What would a clampmeter indicate if clipped around a 3 core cable that is known to be carrying 100 A AC to a motor?

ANSWER

Zero.

This is because the clampmeter monitors the magnetic flux around the cable, which is produced by the current. In a balanced 3-core (or 2-core for that matter) cable, the net flux is zero – therefore no indication. This is why the clampmeter is only connected around a single conductor.

1.12 Live-Line Testers

When equipment is to be inspected for maintenance, it is important that supplies are switched OFF and locked OFF. The equipment must then be PROVED to be dead to eliminate the danger of electric shock. A live-line (or voltage) tester is a simple device that checks only whether or not a voltage exists at terminals.

Live-line testers, up to 500 V, are of various types. Some light up (eg screwdriver type with a neon indicator), some make a noise, others (as shown in Figure 1.14) operate LEDs to indicate the approximate value of voltage.

It is important that voltage testers themselves are PROVED to operate correctly before use. This can be conveniently carried out at the electrical workshop test panel.

Homemade test lamps should not be used as they can be dangerous if protective equipment, eg fuses and finger guards, is not fitted.

Testers with either damaged casing or scratched insulation on the test leads should never be used as they can be dangerous to personnel.

Great care is required with high voltage circuits, where a special HV test probe must be used (see Chapter 8).

1.13 General Electrical Maintenance

All equipment is subject to wear and tear and will eventually reach the end of its useful life and need to be replaced. As equipment nears the end of its safe working life, its condition can deteriorate to a dangerous extent.

The purpose of maintenance, therefore, is to extend the useful life by repair and/or replacement of defective parts and to maintain it in a safe and serviceable condition.

The marine environment is particularly arduous for electrical equipment due to the damp, salt-laden

Figure 1.14 - Live-line tester

atmosphere, extremes of temperature and constant vibration. Shipboard equipment is in particular need of correct maintenance.

The continuous operation of equipment on board ship demands high efficiency and optimum economy to help keep operational costs to a minimum.

An efficient electrical engineer (or chief engineer if there is no electrical engineer on board) must get to know the ship's power system and its equipment. The ship's technical library must be kept in order and be updated to the actual condition of onboard applications. Electrical services and equipment must be kept under continuous observation so that normal healthy operating conditions become known and abnormal operation becomes quickly apparent. Faults should be pinpointed and corrected before a breakdown occurs.

Maintenance can be classified as:

- Breakdown maintenance
- planned maintenance
- condition monitoring.

Breakdown maintenance (corrective maintenance)

This is when equipment is left untouched until a breakdown occurs. At this time, the equipment is repaired or replaced and any other specified maintenance procedure carried out.

There are several disadvantages to breakdown maintenance:

✕ A serious breakdown of equipment may cause enough downtime to put the ship out of commission until it is repaired

✕ if several breakdowns occur simultaneously, the available manpower, skills of the crew or knowledge in the field of the breakdown may not be sufficient to cope adequately, resulting in more delays

✕ some items of equipment may need the specialist services of the manufacturer to carry out repairs, which are expensive and may cause further delays.

Planned maintenance (preventive maintenance)

This is when equipment is regularly inspected and maintained according to a manufacturer's timetable and described procedures that specify the actual work to be done to prevent equipment failure.

Planned maintenance is carried out at fixed regular intervals, whether the equipment needs it or not. The aim is to prevent breakdown and this type of maintenance has the following advantages:

- Fewer breakdowns and reduced downtime produces higher levels of operating efficiency
- maintenance is carried out at times favourable to the operation of the ship
- more effective labour utilisation because maintenance is carried out at times favourable to the ship's staff
- replacement equipment can be ordered in advance
- equipment is maintained in a safe condition with reduced possible dangers
- where a specialist manufacturer's services are required, these can be obtained at convenient times to suit the ship operation
- spare parts required for repair can be ordered in advance
- short-life components are replaced at scheduled intervals.

Condition monitoring (preventive maintenance)

This is when equipment is regularly monitored and tested. When monitoring indicates that a breakdown is imminent, the equipment is repaired or replaced and any other specified maintenance procedures are carried out. Regular insulation testing and vibration testing are two forms of condition monitoring.

Condition monitoring is also carried out at fixed regular intervals. The aim is to forestall breakdown by predicting probable failure from the trend shown by the monitoring results.

The advantage of this type of maintenance is that equipment is not subjected to unnecessary maintenance.

Equipment is regularly condition monitored according to a monitoring schedule. Measurements are taken of insulation resistance, temperature and vibration (of motors). Contacts and other parts subject to deterioration are inspected.

All findings are recorded in an historical record file. No maintenance is carried out until the trend of test results indicates that it has become necessary. The equipment is then either replaced, repaired or subjected to a major overhaul, as specified on a job card.

A maintenance records system is required. The recorded measurements of insulation resistance may show a falling trend, indicating a progressive degradation of insulation. The equipment should be inspected and repaired before the insulation resistance falls to a dangerously low value.

Hot spot temperatures emitted from live electrical equipment can be monitored from a safe distance using an infrared detector or camera.

The recorded measurements of the vibration of a motor may follow a rising trend, indicating progressive bearing deterioration. Bearings should be replaced before failure occurs. Immediate repair or maintenance is probably not necessary but should be put in hand at the earliest convenient moment.

1.14 Fault Finding

Generally, fault finding is not an easy task and it is essential to have a good understanding of the operation of the particular equipment and a general insight into some of the diagnostic skills used to solve the problem.

Planning
A good fault-finder has a well-planned strategy. The evidence is carefully considered before deciding what action to take.

A good diagnostician will use:

- Memory
- logical thinking
- perception
- spatial/mechanical ability
- persistence.

Background (underpinning) knowledge
Knowledge and experience are essential, including knowledge of components, methods and systems together with their operational characteristics.

Fault charts
A list of typical symptoms and faults for a particular equipment plus suggested remedies. These lists should be updated according to experience to show the most probable faults.

FACERAP
The seven letters of the mnemonic FACERAP are the key steps to logical fault finding:

F	(fault)	the name and classification of a fault
A	(appearance)	the description of the fault or its related symptom
C	(cause)	the operational reason for the fault
E	(effect)	the consequential effect of the fault
R	(responsibility)	the correct person to take remedial action
A	(action)	the standard procedure adopted to rectify the fault
P	(prevention)	the procedure to avoid repetition of the fault.

Search strategy

A six-step approach should be utilised:

1. Collect evidence (stop and think).
2. Analyse evidence (check assumptions).
3. Locate fault (inspect and test).
4. Determine and remove cause.
5. Rectify fault.
6. Check system.

Chapter Two
Electrical Distribution

2.1 Power Distribution System

The function of a ship's electrical distribution system is to safely convey the generated electrical power to every item of consumer equipment connected to it. The most obvious element in the system is the main distribution centre, ie the ship's main switchboard. The main board supplies bulk power to motor group starter boards (often part of the main board), section boards and distribution boards. Protection, eg circuit breakers and fuses strategically placed throughout the system, automatically disconnects a faulty circuit within the network. Transformers interconnect the high voltage and low voltage distribution sections of the system.

The operational state of a distribution system is constantly monitored by the power management system for active and reactive load sharing, voltage, current and frequency (power factor is also often monitored). Protection appliances monitor for over and undervoltage, overcurrent, over and under frequency, reverse power and earth faults.

The required electrical services are broadly considered as main and emergency supplies.

Main supply

A ship's electrical distribution scheme generally follows shore practice. This allows normal industrial equipment to be used on board ship after being 'marinised', where necessary, to withstand the rigours of a sea life (eg it must withstand the vibration, humidity, high temperature, ozone, seawater, etc that are likely to be encountered in various parts of the ship).

The majority of ships have a three-phase AC, 380 V, 50 Hz (440 V, 60 Hz) insulated neutral system. This means that the neutral point of a star-connected generator's stator winding is not earthed to the ship's hull. For ships built in Europe, a 380 V, three-phase system is common.

Note: Three-phase AC 380 V, 50 Hz earthed neutral systems can also be found on board. In this type of system, the generator's neutral point is connected to the neutral busbar in the main switchboard which, in turn, is connected to the ship's hull.

The earthed connection for the neutral busbar extends from both ends of the main switchboard sections by means of power conductors, the size of which depends upon the power output.

Ships with very large electrical loads have generators operating at high voltages (HV) of 3.3 kV, 6.6 kV and even 11 kV. Such high voltages are economically necessary in high power systems to reduce the size of current, and so reduce the size of conductors and equipment required. Operating at such high voltages is becoming more common as ship size and complexity increase. 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 or earthing transformer to the ship's hull. The frequency of an AC power system can be 50 Hz or 60 Hz. In Europe and most of the world, the national frequency is 50 Hz, but it is 60 Hz in North America and in a few other countries. The most common power frequency adopted for use on board ships and offshore platforms is 60 Hz. This higher frequency means that motors and generators run at higher speeds, with a consequent reduction in size for a given power rating.

Lighting and low power single-phase supplies operate at the lower voltage of 220 V, which is derived from power step-down transformers connected, with their primary windings, to the 380 V (440 V) system.

The electrical energy is routed through the main switchboard, then distributed via cables to section and distribution boards, and ultimately to the final load consumers.

The circuit breakers and switches are the means of interrupting the flow of electric current. The fuses and relays protect the distribution system from the damaging effects of large fault currents.

Figure 2.1 shows an HV/LV layout of a ship's distribution system. The system is called a radial, or branching, system and it has a simple and logical structure. Each item of load is supplied at its rated voltage via the correct size of cable and is protected by the correctly rated protection device.

The main electrical load is divided into essential and non-essential services.

Essential services are for the safety of personnel and for the safe navigation and propulsion of the ship and they may be supplied directly from the main switchboard or via section boards or distribution boards. Emergency supplies are necessary for loads required to handle a potentially dangerous situation.

To maintain generator operation during an overload, a preferential load shedding arrangement is employed. This is achieved by an analogue current monitoring relay, called a preference trip relay.

If a generator overload develops, the preference trip relay sets an alarm and acts to trip selected non-essential loads. This reduces the generator load so that it may continue to supply essential circuits, maintaining its nominal load.

Each generator has its own overcurrent relay to trip its own circuit breaker, which is typically high set at 150% with a 20 second delay.

In addition, each generator has its own preference overload trip, which is low set, generally at 110% current with instantaneous operation.

If a generator overload condition develops, the power management system (PMS) disconnects non-essential services in a defined order at set time intervals, eg:

- 1st trip – air conditioning, ventilation, galley and laundry services – 5 seconds
- 2nd trip – reefer container sockets on board a container vessel or refrigerated cargo plant on board a reefer carrier – 10 seconds.

The order of tripping varies with the ship type. When sufficient non-essential load has been

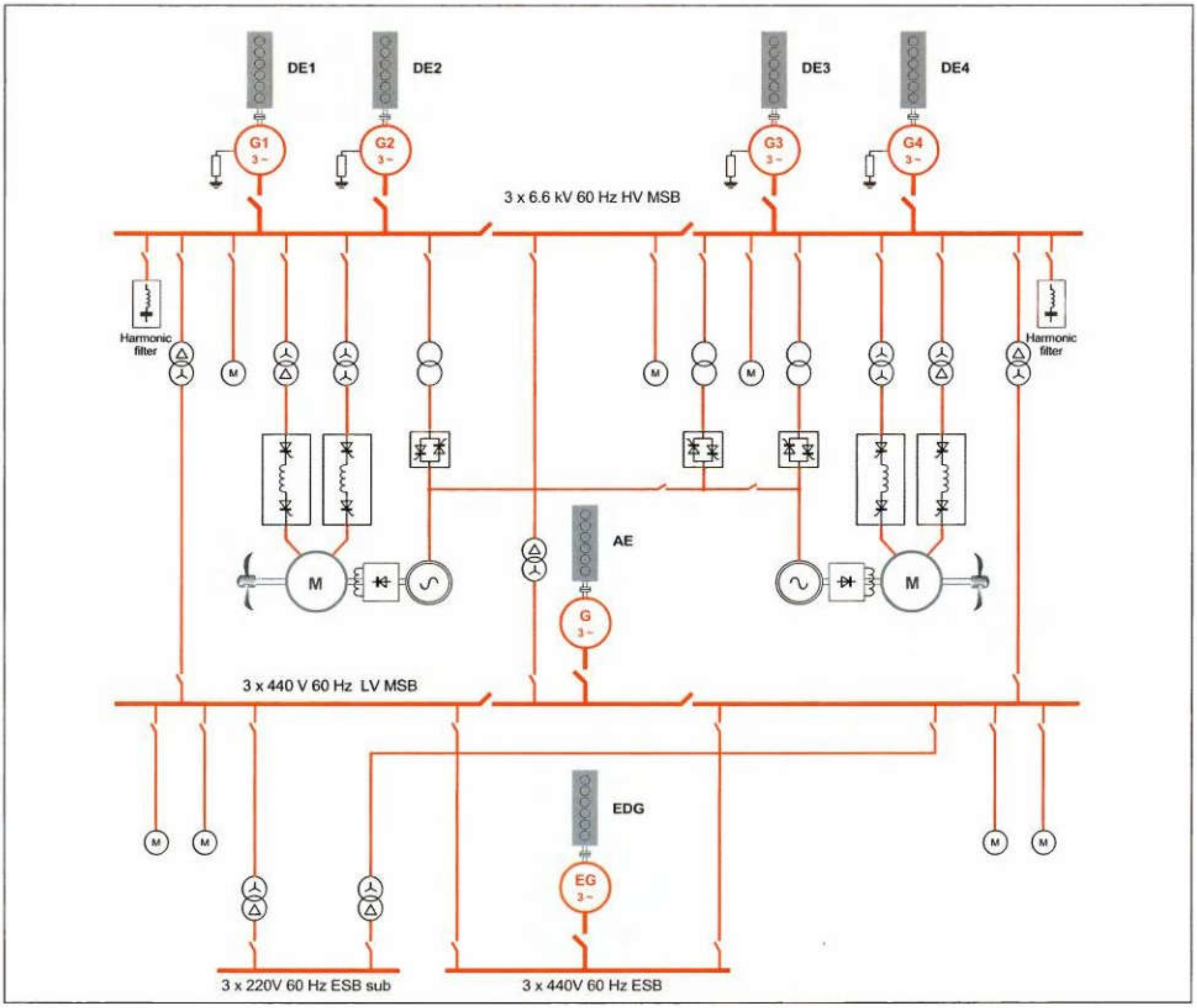


Figure 2.1 - HV/LV power system

disconnected, the preference overload trip resets and no further load is disconnected.

The generator preference trip system can also be initiated by the frequency monitoring relay in the event of under-frequency (eg due to decreasing the speed of the generator's prime mover).

In the majority of cases, the preference trip protection is incorporated into a combined electronic relay (or programmable logic control-based PMS) that also monitors generator over and undervoltage, overcurrent and reverse power.

To maintain either the preference relay trip or the PMS-initiated safety trips' settings as originally specified, they must be periodically checked when the register survey is carried out.

Emergency supply

An emergency electrical power service must be provided in the event of a main power failure. This is for emergency lighting, alarms, communications, watertight doors and other services necessary to maintain safety and permit safe evacuation of the ship.

Regulations require that the emergency power source is a generator, batteries or both. The emergency power source must be self-contained and not dependent upon any other engine room power supply. A battery, when fully charged, is self-contained. An emergency generator must have an internal combustion engine as prime mover and have its own fuel supply tank, starting equipment and switchboard in the near vicinity.

The emergency supply should automatically operate as quickly as possible but not later than 45 seconds after the failure of the main source of power. Emergency batteries should be arranged so that they are switched into service immediately following a main power failure. Emergency generators can be hand cranked, but are usually automatically started by compressed air or a battery to ensure immediate run-up following a main power failure. Other cranking options should be provided to ensure safety, eg cranking by means of the electric starter driven with a set of batteries or with a hydraulically driven starter accompanied by a hand-driven pump and hydraulic accumulator.

Although regulations may permit a battery to be the sole source of emergency power, in practice a suitable battery may be physically very large and so a diesel-driven generator is usually installed, with its own starting battery large enough to sustain several consequent starting attempts or to air start (hydraulic start) supply.

Another set of batteries should also be installed locally to supply automation, the alarm system, navigation aids and the ship's communication equipment (such as GMDSS).

On passenger ships, SOLAS Chapter II-1, Part D, requires that the primary emergency power supply is provided by a diesel-driven generator for up to 36 hours (18 hours for non-passenger vessels). In addition, an emergency transitional battery must also be installed to maintain vital services (mainly lighting) for a short period – typically a minimum of 3 hours. This emergency battery is to ensure that a total blackout cannot occur in the transitional period between loss of main power and the connection of the emergency generator.

A typical distribution system, incorporating emergency power supplies, is shown in Figure 2.2.

There is no standard electrical supply arrangement as all ships differ in some respect. Both the main and the emergency consumers are supplied by the main service generators during normal operating conditions. In the event of an emergency, only the emergency services are supplied by the emergency generator.

The emergency power system must be ready and available at all times and this level of reliability requires special care and maintenance. The system must be tested at regular intervals to confirm that it does operate correctly. The testing is normally carried out during the weekly emergency fire and boat drill practice sessions. The main generators are not shut down, but the emergency power sources are energised and connected to supply the emergency services for the period of the practice session.

The emergency generator may be used as the main power supply during lay time (either in single mode or in parallel with one of main generators). Independence of the emergency power supply from other auxiliaries of the main engine plant must be ensured.

The regulations governing the emergency source of power are detailed in SOLAS, national regulations and in the Classification Societies' rules.

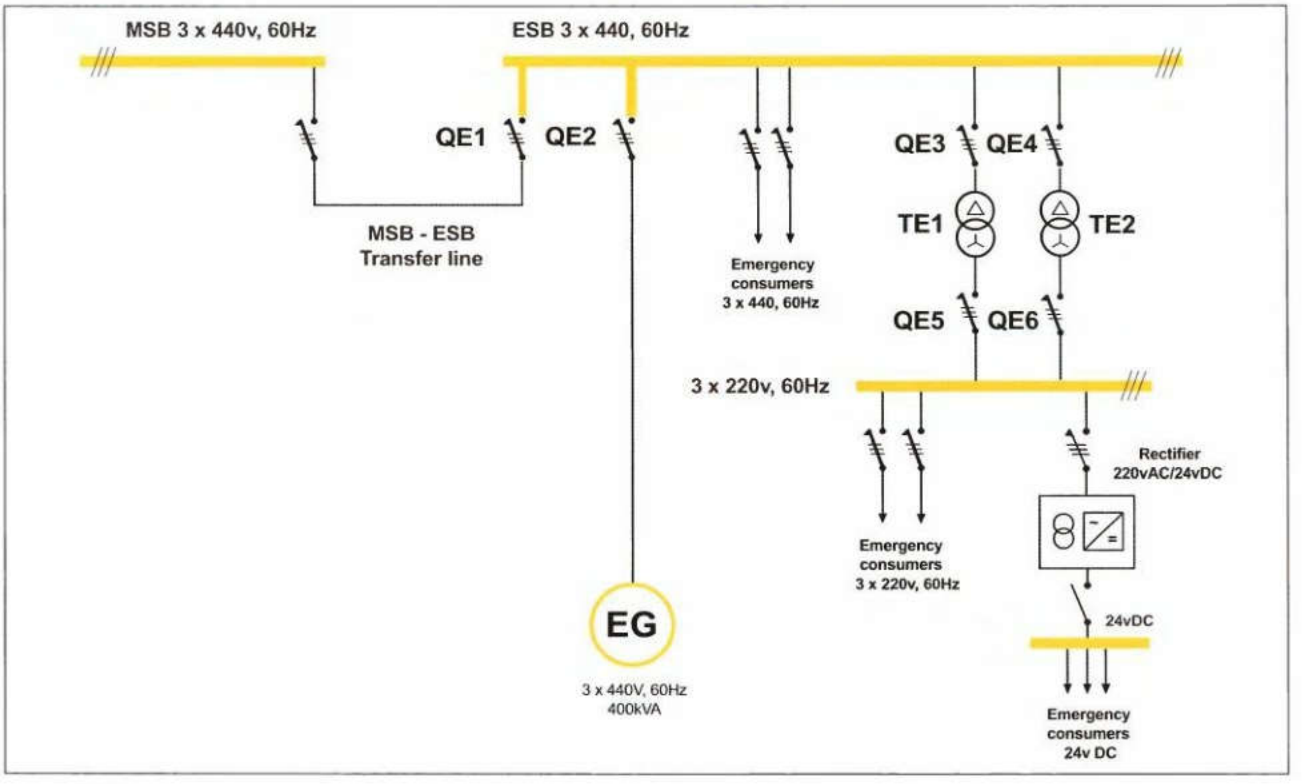


Figure 2.2 - Emergency power supplies

2.2 Insulated and Earthed Neutral Systems

An insulated system is one that is totally electrically insulated from earth (ship's hull).

An earthed system has the supply neutral point connected to earth.

Shipboard main LV systems at 380 V AC and 440 V AC are normally insulated from earth (ship's hull), although earthed neutral systems can also be encountered. Similar systems ashore are normally earthed to the ground. HV systems (≥1000 V) are usually earthed to the ship's hull via a neutral earthing resistor (NER) or through a high impedance transformer to limit earth fault current.

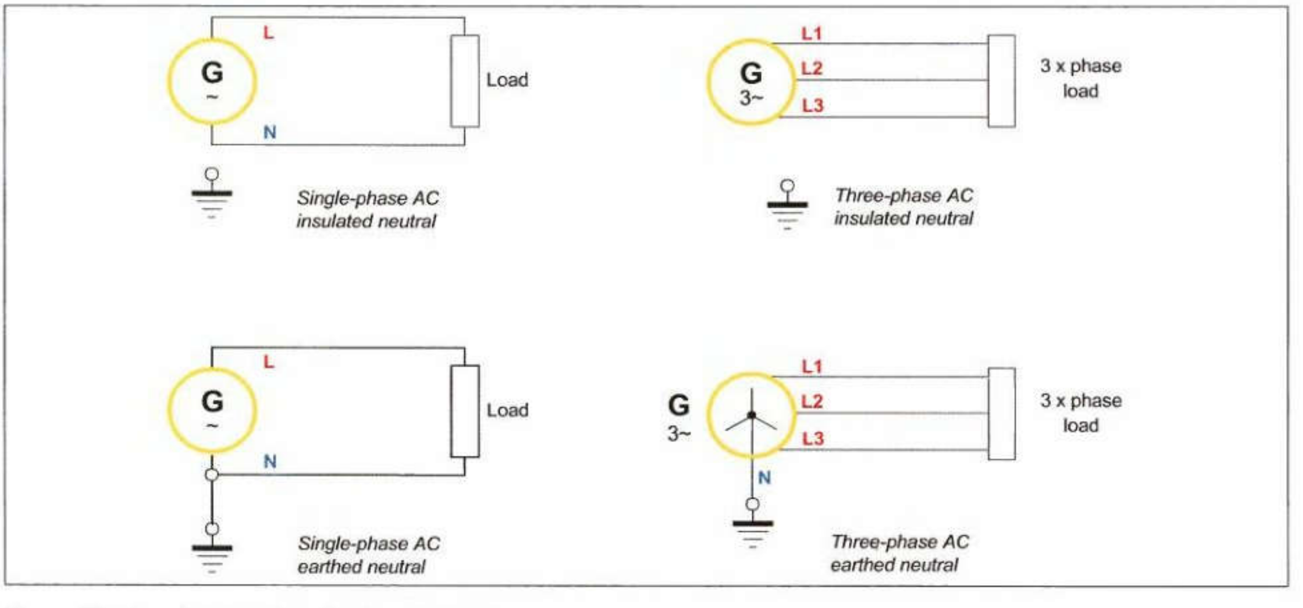


Figure 2.3 - Insulated and earthed neutral systems

The priority requirement on board ship is to maintain continuity of the electrical supply to essential equipment in the event of a single earth fault occurring.

A circuit consists of two parts:

- Conductor, which carries current through the circuit
- insulation, which keeps the current inside the conductor.

Three basic circuit faults that can occur are shown in Figure 2.4(b):

- An open-circuit fault is due to a break in the conductor, as at A, so that current cannot flow
- an earth fault is due to a break in the insulation, as at B, allowing the conductor to touch the hull or an earthed metal enclosure
- a short-circuit fault is due to a double break in the insulation, as at C, allowing both conductors to be connected so that a very large current by-passes, or short-circuits, the load.

The size of fault current that will occur depends on the overall impedance left in the circuit under fault conditions.

The majority of earth faults occur within electrical equipment due to an insulation failure or a loose wire, which allows a live conductor to come into contact with its earthed metal enclosure.

To protect against the dangers of electric shock and fire that may result from earth faults, the metal enclosures and other non-current carrying metal parts of electrical equipment must be earthed. The earthing conductor connects the metal enclosure to earth (the ship's hull) to prevent it from attaining a dangerous voltage with respect to earth. Such earth bonding of equipment ensures that it always remains at zero volts.

QUESTION

A 10 A motor operates from a 220 V *insulated* system. The supply cables have a total impedance of 0.01 Ω.
If:

(a) an open-circuit fault

(b) an earth fault, and

(c) a short-circuit fault

occurred, what circuit current would flow in each case?

ANSWER

(a) the open-circuit fault has infinite impedance, so:

$$I = \frac{V}{Z} = \frac{220\ V}{\infty\Omega} = ZERO$$

(b) the earth fault has *NO* effect on the circuit current, so I remains at 10 A (because this is an **insulated** system)

(c) the short-circuit fault impedance is limited only by the 0.0 1Ω of the cables, so:

$$I_{sc} = \frac{V}{Z} = \frac{220\ V}{0.01\ \Omega} = 22{,}000\ A \quad or \quad 22\ kA$$

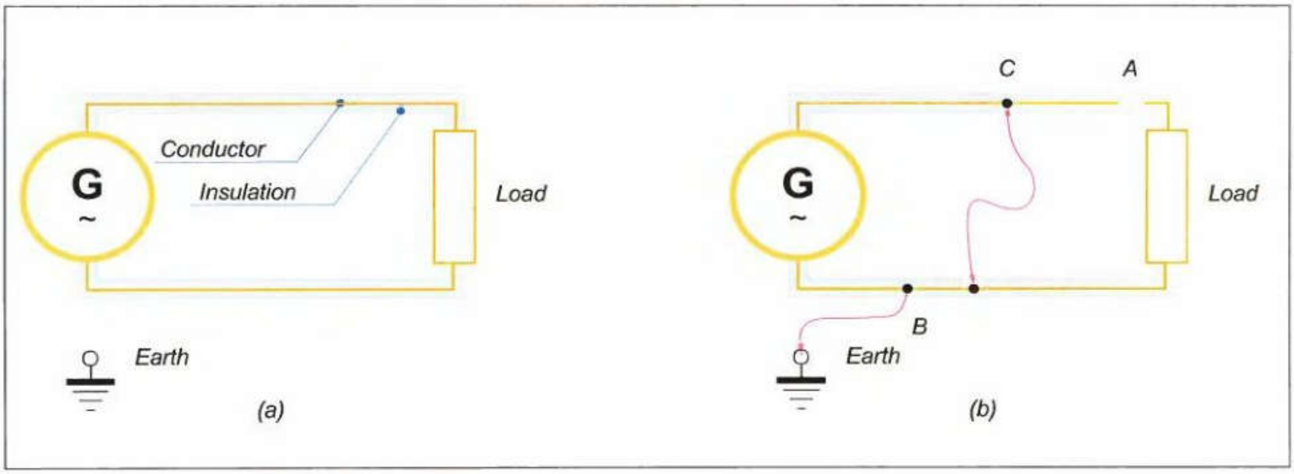


Figure 2.4 - Circuit faults

2.3 Significance of Earth Faults

If a single earth fault occurs on the live line of an earthed distribution system, it would be equivalent to a short-circuit fault across the generator through the ship's hull. The resulting large earth fault current would immediately cause the line's protective device (fuse or circuit breaker) to trip out the faulty circuit. The faulted electrical equipment would be immediately isolated from the supply and so rendered safe. However, the loss of power supply could create a hazardous situation, particularly if the equipment was classed essential, eg steering gear. The large fault current could also cause arcing damage at the fault location.

By contrast, a single earth fault 'A' occurring on one line of an insulated distribution system will not cause any protective trip to operate and the system would continue to function normally, as shown in Figure 2.5.

This is the important point: equipment continues to operate with a single earth fault as it does not provide a complete circuit so no earth fault current will flow.

If a second earth fault at 'B' occurred on another line in the insulated system, the two earth faults together would be equivalent to a short-circuit fault (via the ship's hull) and the resulting large current would operate protection devices and cause disconnection of, perhaps, essential services, creating a risk to the safety of the ship.

An insulated distribution system, therefore, requires two earth faults on two different lines to cause an earth fault current to flow.

An insulated system is, therefore, more effective than an earthed system in maintaining continuity of supply to essential services, which is why it is used for most marine electrical systems.

High voltage systems (3.3 kV and above) on board ship are normally earthed via a resistor connecting the generator neutrals to earth, as shown in Figure 2.6.

The ohmic value of each earthing resistor is usually chosen so as to limit the maximum earth fault current to not more than the generator full load current. Such a neutral earthing resistor (NER) is usually assembled from metallic plates. The use of such an earthed HV system means that a single earth fault will cause current to flow in the neutral connection wire. This is monitored by an earth fault (E/F) relay to create alarm and trip functions.

Certain essential loads (eg steering gear) can be supplied via a transformer, with its secondary winding unearthed to maintain security of supply in the event of a single earth fault.

Regulations insist that tankers have only insulated distribution systems. This is intended to reduce danger from earth fault currents circulating in the hull within hazardous zones, which may cause an explosion of the flammable cargo.

An exception allowed by regulating bodies occurs where a tanker has a 3.3 kV earthed system. Such a system is permitted providing that the earthed system does not extend forward of the engine room bulkhead and into the hazardous area.

Electrical supplies forward of the engine room bulkhead are usually three-phase 440 V insulated

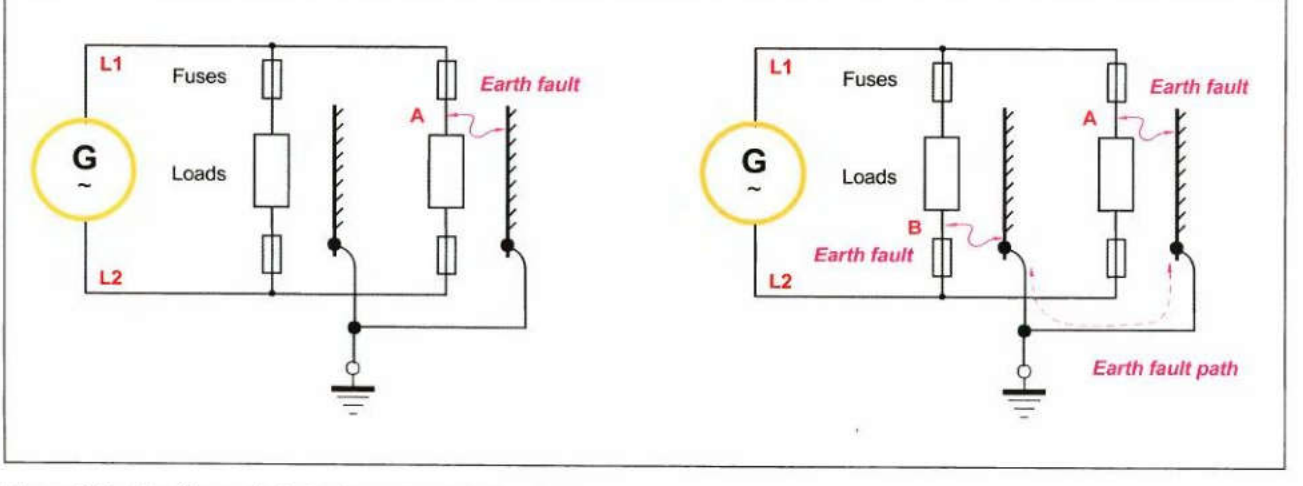


Figure 2.5 - Double earth faults in an insulated system

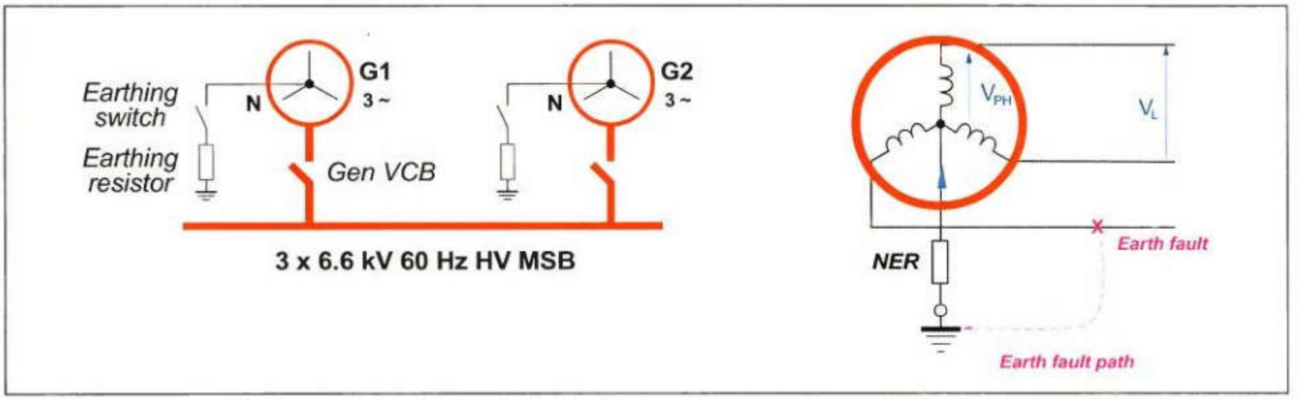


Figure 2.6 - Neutral earthing in HV system

and obtained from a three-phase 3.3 kV/440 V power step-down transformer.

An earth fault monitor should be fitted to the main and emergency switchboards to indicate the presence of an earth fault on each isolated section of a distribution system, eg on the 440 V and 220 V sections. An earth fault monitor can be either a set of indicator lamps or an instrument (or both) to show the system IR value to earth.

Earth indication lamps in a three-phase AC system are arranged as shown in Figure 2.7. When the system is healthy (no earth faults), the lamps glow with equal half brilliance. If an earth fault occurs on one line (as illustrated in the line 3 earth fault example in Figure 2.7), the lamp connected to that line goes dim or is extinguished (in the case of a short-circuit to the earth). The other lamps experience an increased voltage so will glow brighter than before.

Earth indication lamps have been the most common method used for many years and are an inexpensive installation that is easy to understand. Their major disadvantage is that they are not very sensitive and will not indicate the presence of a high impedance earth fault. This has led to the development and use of earth fault indicator instruments.

One common type of earth fault monitor connects a small DC voltage to the distribution system. Any resulting DC current is a measure of the insulation resistance of the system.

The injection-type instrument limits the maximum earth fault monitoring current to only 1 mA (compared with about 60 mA for earth lamps), and the meter indicates insulation resistance directly in kΩ or MΩ. The monitor triggers an alarm when its set value is reached.

This type of arrangement has been developed to meet regulations that demand that circuits in or passing through hazardous zones must be continuously monitoring the system insulation resistance. Visual and audible alarms are given if the insulation resistance falls below a pre-set value.

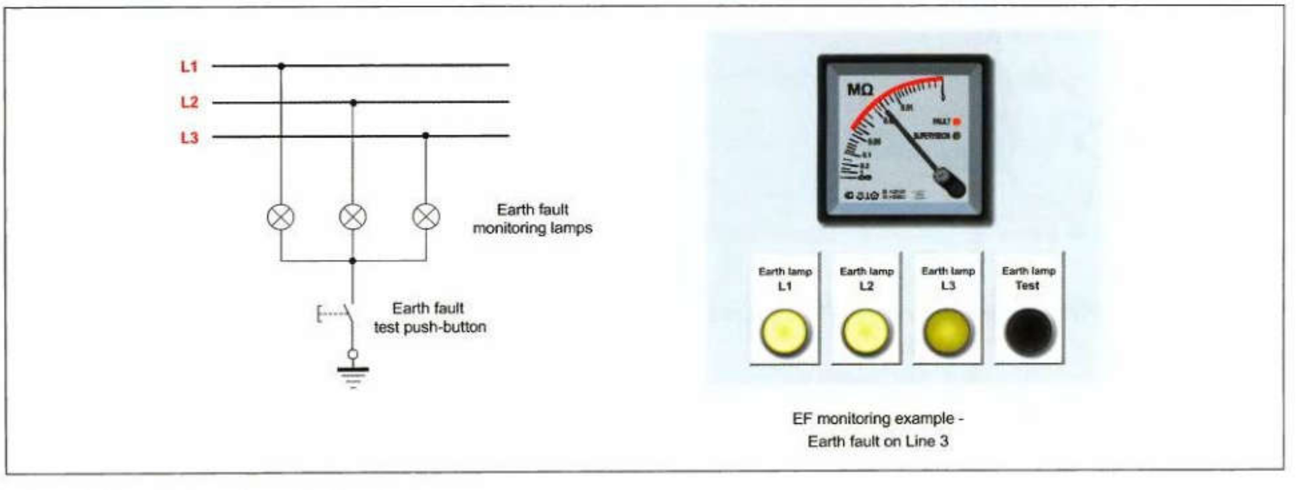


Figure 2.7 - Earth fault monitoring with lamps

QUESTION

What would be the ohmic value of an NER to limit the earth fault current to the full load rating of a 2 MW, 0.8 pf, 3.3 kV, three-phase AC generator?

ANSWER

In a three-phase system: $P = \sqrt{3} \times V_L \times I_L \times \cos\varphi$
where V_L is line voltage (3.3 kV),
I_L is the line current and $\cos\varphi$ is the power factor.

The generator full load current is:

$$I_L = \frac{2{,}000{,}000}{\sqrt{3} \times 3{,}300 \times 0.8} = 437\ A$$

Under E/F conditions, a phase voltage of:

$$V_{PH} = \frac{3{,}300}{\sqrt{3}} = 1905\ V$$ drives the fault current

through the NER. So its ohmic value has to be:

$$\frac{1905\ V}{437\ A} = \mathbf{4.4\ \Omega}$$

An HV system (1 kV – 11 kV) is usually earthed at the generator neutral point via an NER. This arrangement allows the neutral (and therefore the earth fault) current to be monitored for alarm/trip by a current transformer (CT) and E/F relay.

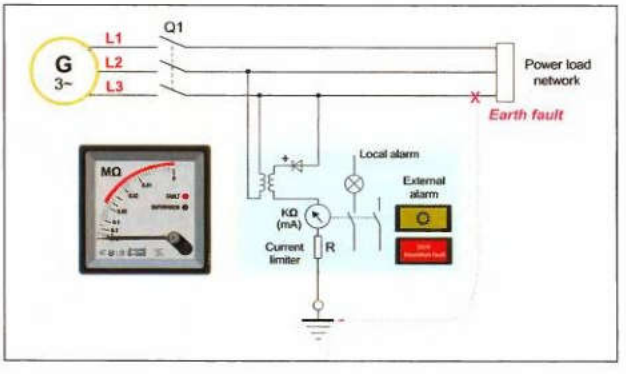


Figure 2.8 - Earth fault monitoring by DC injection

Alternatively, a special three-phase earthing transformer is connected to the HV system busbars. This high impedance earthing transformer is arranged to limit the maximum permitted E/F current and initiate an alarm/trip voltage signal to a connected protection relay.

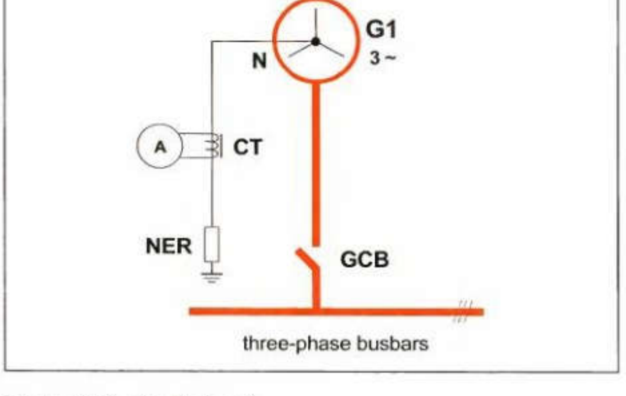


Figure 2.9 - NER circuit

Measurement of the earth fault current in an earthed system can be provided in a number of ways and one method is shown in Figure 2.10.

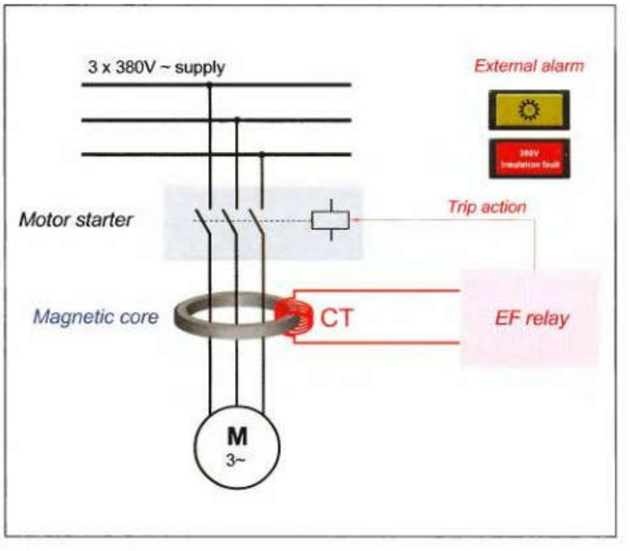


Figure 2.10 - Core balance CT

Here, the current transformer (CT) measures the phasor sum of the three line currents supplied to the motor. If the motor is healthy (no earth faults), the phasor sum of the currents measured by the CT is zero.

If an earth fault (E/F) occurs in the motor, an E/F current flows and the phasor sum of the currents is no longer zero. The current monitored by the E/F relay is used to trip the contactor in the starter to isolate the faulty motor circuit.

The earth fault monitor on the switchboard shows the presence of an earth fault on the distribution system. It is up to the maintenance staff to trace (search for) the exact location of the fault and then to clear it as quickly as possible.

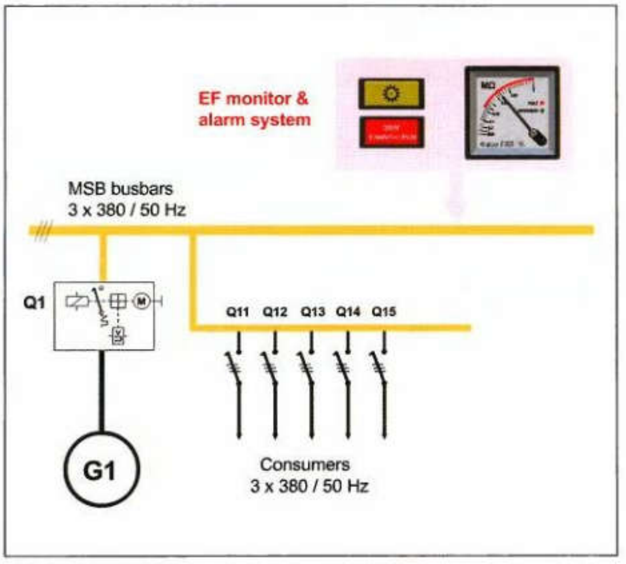


Figure 2.11 - Earth fault monitors in a distribution system

A simple method would be to open the circuit breakers feeding loads Q11, Q12, Q13, etc (as shown in the distribution system in Figure 2.11), one at a time, and watch the earth fault monitor while observing which circuit breaker, when opened, clears the earth fault. The earth fault must then be on that particular circuit.

In practice, circuits cannot be randomly disconnected in this way. Some vital service may be interrupted, such as causing the main engines to stop, possibly in dangerous narrow waters. Therefore, tracing the earth fault must be coordinated with the operational requirements of the ship's electrical services.

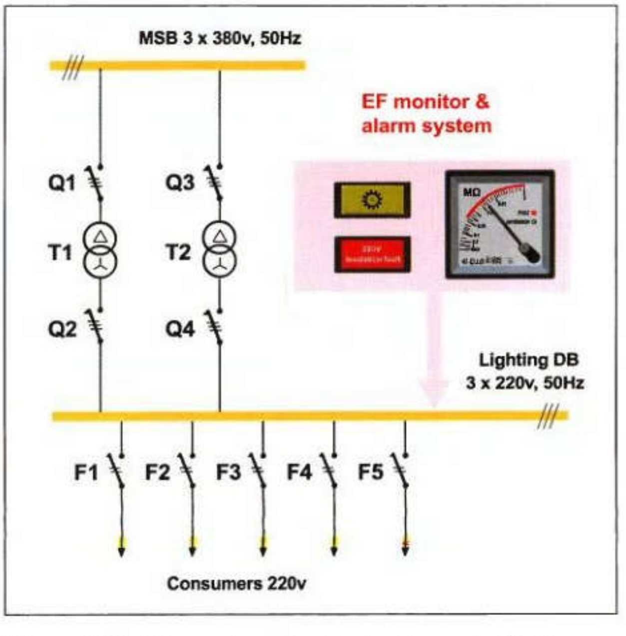


Figure 2.12 - Three-phase to single-phase distribution

The method of earth fault clearance will be described fully for an example lighting distribution circuit, as shown in Figure 2.12.

If the earth fault monitor on the 220 V lighting distribution board (DB) indicates the presence of an earth fault, miniature circuit-breakers F1, F2, F3 and F4 are sequentially opened and closed in turn until the earth fault monitor indicates the earth faulted circuit.

If this is circuit breaker F2, which supplies a distribution fuse board (DFB) for lighting circuits, then, as there is no earth fault monitor, an IR tester must be used to determine which is the faulty lighting circuit.

At this DFB, fuse-pair No. 1 (CCT1) is removed to isolate the supply to the load (Figure 2.13).

The IR tester (megger) is now connected with one lead to earth (hull) and the other lead to 'b' (the outgoing terminal as shown), and a test applied. If healthy (IR > 1 MΩ), connect the test lead to 'a' and repeat the test. If both 'a' and 'b' are healthy, circuit 1 is healthy and fuse-pair 1 can be replaced.

Fuse-pair 2 (CCT2) is now removed and tested at 'a' and 'b' in a similar manner. If an earth fault is indicated (IR = low) then the faulted circuit has been located.

All fuse-pairs are checked in turn to confirm whether healthy or faulted.

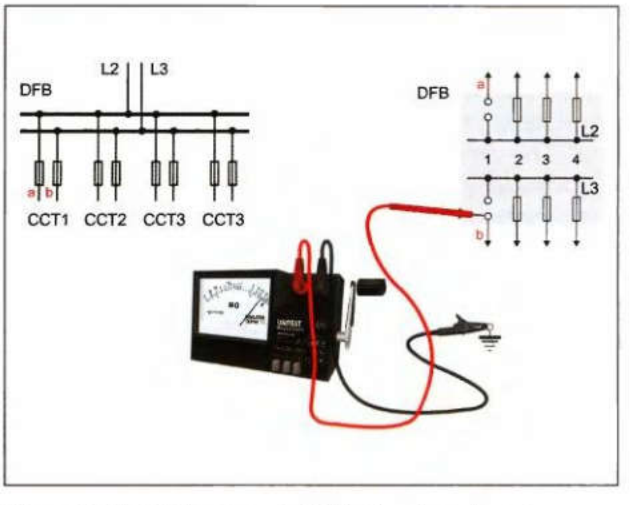


Figure 2.13 - TR testing at distribution fuse board

When testing IR at the faulted circuit, the fuses should be removed, all switches should be opened and all lamps taken out, as shown in Figure 2.14.

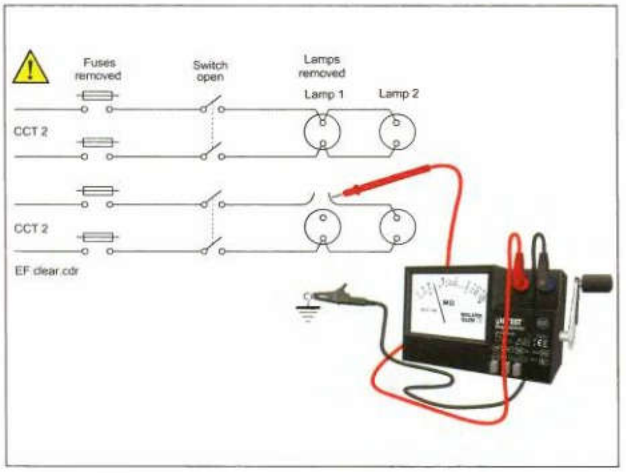


Figure 2.14 - IR test on a lighting circuit

This breaks the circuit into several isolated conductor sections.

At the supply distribution board, test at 'a' and then at 'b'. If both have an IR > 1 MΩ then the conductors connected to 'a' and 'b' are clear and healthy. Close the switch and re-test at 'a'. If the IR is low then the earth fault lies on the conductors beyond the switch.

At lamp 1, remove the fitting and disconnect the conductors as shown to further break down the circuit. Use the IR tester on each of these disconnected leads. If one conductor is indicated as having an earth fault (suppose it is the conductor between lamp 1 and lamp 2) then the earth fault lies at lamp 1 or lamp 2 or on the conductor.

Both lamp fittings must now be opened and visually inspected to trace the exact location of the earth fault. The method of tracing the earth fault is that of continually breaking down the circuit into smaller and smaller sections until it is finally located.

When located, the damaged insulation must be repaired. The method of repairing the earth fault depends on its cause and this is determined by visual examination.

A lamp fitting that is damaged must be replaced. Dampness in insulation must be dried out by gentle heat and then some precaution must be taken to prevent the future ingress of moisture.

Insulation that has been mechanically damaged or weakened by overheating must be made good again. If surface dirt is the cause, a thorough cleaning will usually cure the fault.

2.4 Distribution Circuit Breakers

Details of main circuit breakers for main generators and main feeder circuits are included in Chapter 3.

The function of any circuit breaker (CB) is to safely make onto and break open the prospective short-circuit fault current expected at that point in the circuit. The main contacts must open rapidly while the resulting arc is transferred to special arcing contacts above the main contacts. Arc chutes with arc splitters quickly stretch and cool the arc until it snaps. The CB is open when the arc is quenched.

Feeder and distribution circuits are usually protected by moulded-case (MCCB) or miniature (MCB) circuit breakers.

MCCBs

These are compact air circuit breakers fitted in a moulded plastic case. They have a lower normal current rating (50-1500 A) than main breakers and a lower breaking capacity (see Figure 2.15).

Figure 2.15 - MCCB

They usually have an adjustable thermal overcurrent setting and an adjustable or fixed magnetic overcurrent trip for short-circuit protection built into the case. An undervoltage trip coil may also be included within the case.

Operation to close is usually by a hand-operated lever, but motor-charged spring closing gear can also be fitted. MCCBs are reliable, trouble free and require negligible maintenance. If the breaker operates in the ON position for long periods, it should be tripped and closed a few times to free the mechanism and clean the contacts. Terminals should be checked for tightness or overheating damage will develop.

The front cover of larger MCCBs (around 1000 A rating) can usually be removed for inspection and cleaning. Following tripping under a short-circuit fault, the breaker should be inspected for damage, checked for correct operation and its insulation resistance measured. A test result of at least 5 MΩ is usually required. Any other faulty operation usually requires replacement or overhaul by the manufacturer.

MCCBs can be used for every application on board ship, from generator breakers to small distribution breakers. The limited breaking capacity may demand that backup fuses be fitted for very high prospective short-circuit fault levels.

MCBs

These are very small air circuit breakers fitted in moulded plastic cases (see Figure 2.16). They have current ratings of 5-100 A and generally have thermal overcurrent and magnetic short-circuit protection. They have a very limited breaking capacity (about 3000 A) and are commonly used in final distribution boards instead of fuses. The DB is supplied via a fuse or MCCB with the required breaking capacity.

Figure 2.16 - MCB

MCBs must be replaced if faults develop – no maintenance is possible.

2.5 Transformers

Electrical generation on board ship is typically at three-phase AC, 440 V, 60 Hz (or 380 V, 50 Hz), while fixed lighting and other low power loads are supplied with 220 V AC single-phase from very efficient (typically > 90%) static transformer units. Ships with HV generation require three-phase transformers to supply the LV engine room and accommodation sub-switchboards, eg using 6600/440 V units (see Figure 2.17).

The principle of operation of a single-phase transformer is straightforward. An applied AC voltage (V_1) to the primary winding sets up an alternating magnetic flux in the laminated steel core.

The flux induces an emf in the secondary, whose size is fixed by the ratio of primary and secondary turns in the pair of phase windings (N_1 and N_2) to give:

$$\frac{V_1}{V_2} = \frac{N_1}{N_2}$$

The secondary voltage V_2 is available to drive current through a load.

It is the load connected to the secondary that sets the size and power factor angle of the load current I_2. This is matched on the primary side from:

$$\frac{V_1}{V_2} = \frac{I_2}{I_1}$$

Transformers are rated in apparent power (VA or kVA) units.

QUESTION

A 440/220 V single-phase transformer supplies a load of 5 kW at 0.8 power factor load.

Calculate secondary and primary currents (ignoring transformer power losses).

ANSWER

From: $P_2 = V_2 \times I_2 \times \cos\varphi$, $I_2 = \dfrac{P_2}{V_2 \times \cos\varphi}$

$$= \frac{5000}{220 \times 0.8} = \mathbf{28.41\ A}$$

$$I_1 = I_2 \times \frac{V_2}{V_1} = 28.41 \times \frac{220}{440} = \mathbf{14.2\ A}$$

or, check from $P_1 = V_1 \times I_1 \times \cos\varphi$

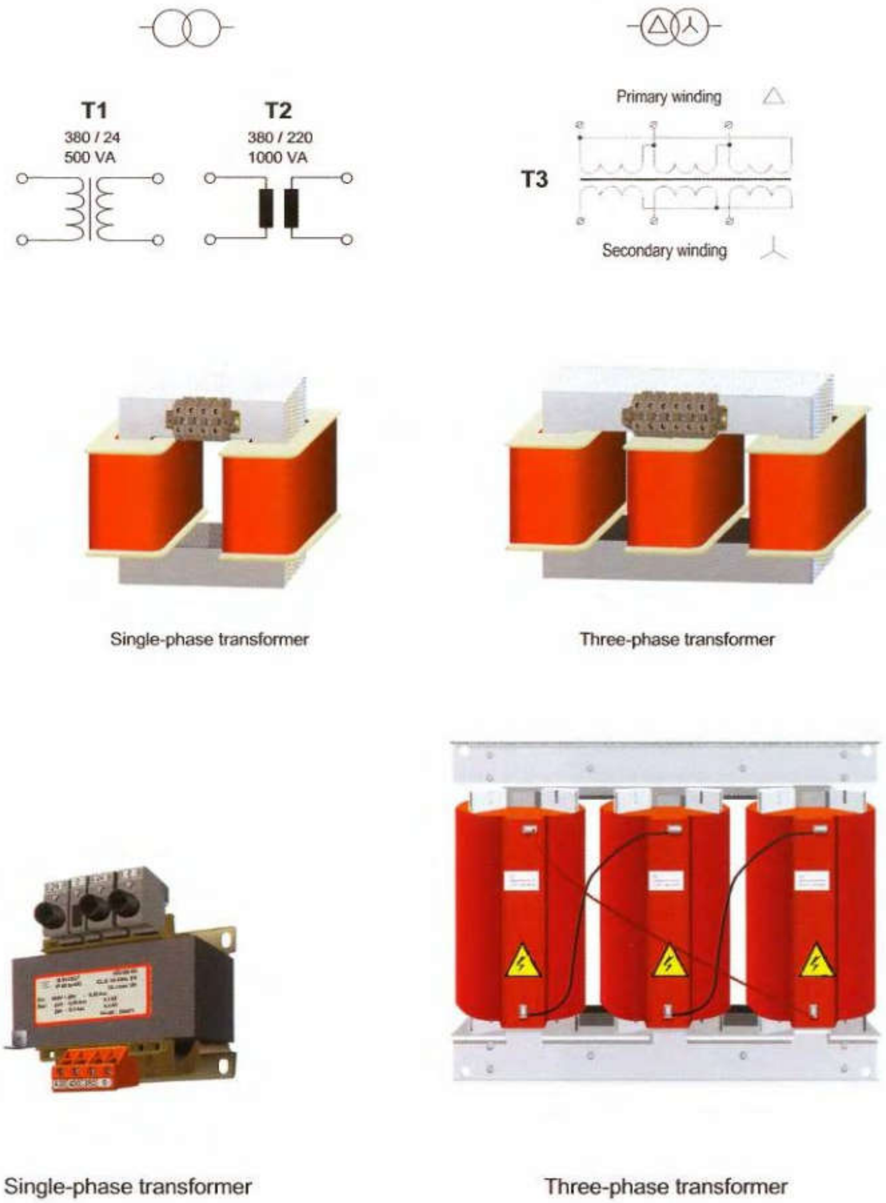


Figure 2.17 - Transformer arrangements

The transformers are generally air cooled and mounted in sheet steel enclosures that are often located adjacent to the main switchboard. Alternatively, they may be fitted within the switchboard so that transformer enclosures are not required.

Three-phase 440/220 V lighting transformers are usually composed of 3 separate single-phase units interconnected to form a three-phase arrangement. This enables easy replacement of a single-phase unit if it develops a fault. The alternative is to use a single three-phase unit with all windings mounted on a common magnetic core. This type has to be completely isolated in the event of a fault on one phase only.

The power transformers for use on three-phase insulated systems are generally interconnected in a delta-delta circuit configuration (other configurations, such as delta-star and star-delta, are also in use) using either copper links or power conductors between the phase windings. An example of the delta-delta transformer arrangement is shown in Figure 2.18.

If a fault develops on one phase of such an arrangement, the faulty unit can be disconnected (via the links) creating an open-delta or 'V' connection and a three-phase supply will still be available, although at a reduced power capacity. This is a useful safeguard.

Two transformers from the main switchboard, as well as two transformers from the emergency switchboard, are usually provided to supply the ship's 220 V consumers in such a way that one transformer is generally strong enough to bear full load while allowing the other unit to remain in standby. This particular arrangement ensures safety in supplying essential consumers (eg emergency lighting, navigation aids, smoke detection system, etc). In the event of the working unit's failure, it will be isolated from the circuit by circuit breakers and the load will be taken by the standby unit.

Transformers for use on three-phase HV/LV earthed systems ashore are generally connected delta-star to provide a three-phase, 4-wire LV supply, eg a 6600/400 V ratio gives a secondary line voltage of 400 V plus a line-neutral phase voltage of $400/\sqrt{3} = 230$ V. An earth fault occurring on such a neutral earthed system will immediately operate the protective fuse or circuit breaker. This interruption of supply leads to rapid identification of the faulty circuit.

Transformers are static items of equipment that are usually very reliable and trouble free. However, like all electrical equipment, transformers must be subject to the usual maintenance checks.

At regular specified intervals, transformers must be switched off, covers removed and all accumulated dust and deposits removed by a vacuum cleaner and suitable brushes. Windings must be inspected for any signs of damage or overheating. Winding continuity resistance values are measured, recorded and compared with each other for balance. Any differences in continuity readings will indicate winding faults, such as short-circuited turns. The insulation resistance of all windings must be measured, both with respect to earth and to the other phase windings. The cause of any low insulation resistance reading must be investigated and rectified. Cable connections must be checked for tightness.

All test results and observations should then be recorded for future reference.

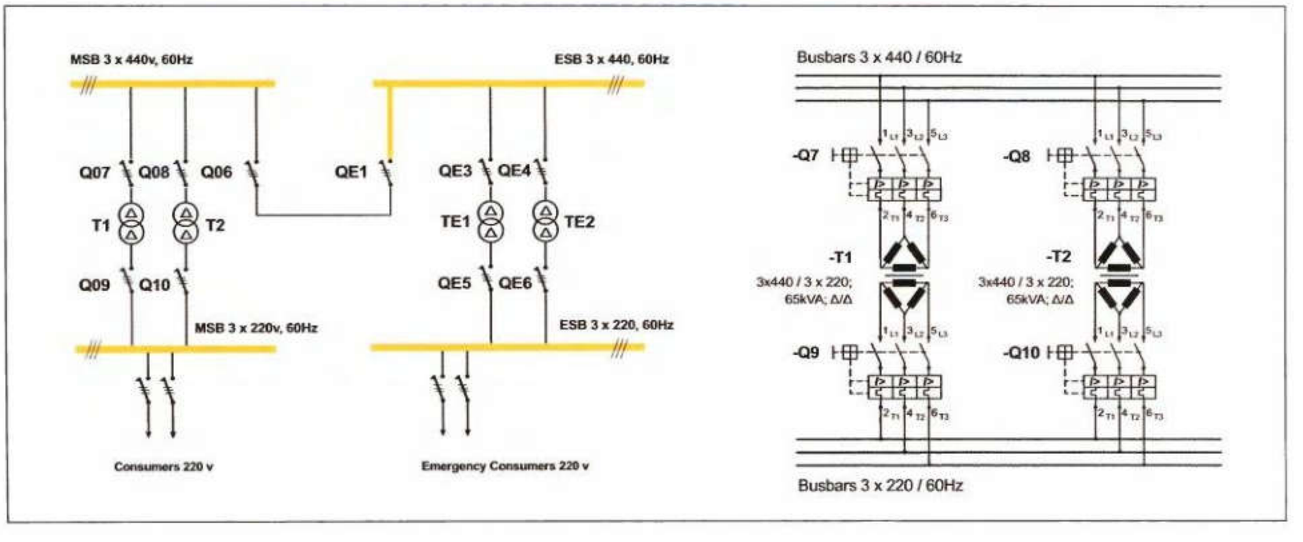
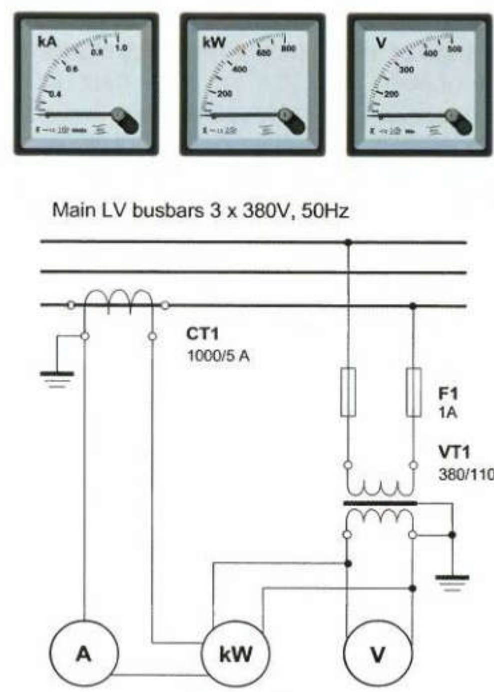


Figure 2.18 - Power transformers connection

2.6 Instrument Transformers

Transformers are used to supply instruments and protection relays with proportionally small currents and voltages derived from the large currents and voltages in a high power network (see Figure 2.19).



Wattmeter has current and voltage inputs

Figure 2.19 - Instrument connections with CT and VT

Voltage transformers (VTs) supply voltmeters and the voltage-operated coils of instruments and relays. A standard secondary voltage of 220 V is used. Current transformers (CTs) supply ammeters and the current-operated coils of instruments and relays with a standardised 5 A or 1 A.

The use of VTs and CTs allows standardised instruments and relays to be used. They also improve safety by providing low voltage and low current isolated supplies for monitoring instruments and protection relays.

VTs are built like small power transformers. They are not normally used at voltages less than 3 kV. CTs can be of the wound primary or bar primary type.

The bar primary type CT is used with very high primary current ratings and the wound primary type is used for small step-down ratios, eg 1000/5 A bar primary; 50/5 A wound primary.

The ratio specified on a VT details its input and output voltages, eg 380 V/220 V is used on a 380 V mains circuit and steps the voltage down to 220 V.

The associated instrument will have its scale calibrated '0-380 V' and will be marked '380 V/220 V VT ratio'.

The ratio specified on a CT similarly details its input and output currents, eg 150/1 A CT is used on a 150 A mains circuit and steps the current down to 1 A. The associated instrument will have its scale calibrated '0-150 A' and will be marked '150/1 A CT ratio'.

The use of instrument transformers does not eliminate danger to operators. The 220 V output from a VT will apply a severe, possibly lethal, shock to unsuspecting fingers!

The secondary circuit of a CT must never be opened while mains primary load current is flowing. Excessive heating will develop in an open circuited CT, with an extremely high voltage arising at the open secondary terminals. If an ammeter is to be removed from circuit, the CT secondary output terminal must be first short-circuited, with the primary circuit switched off. The secondary short-circuit will not damage the CT when the primary current is switched on. For further safety, one end of the secondary winding of a CT or VT is connected to earth.

Miniature indicator lamp fixtures on switchboards are commonly of the transformer type, with a small transformer built into the lamp fitting. The transformer provides a 6 V or 12 V output. The lamp is of low wattage with a small bayonet cap fitting. Although not an accurate instrument transformer, the lamp transformer is similar in function to a VT.

Current transformer for motor starters with a ratio 100/1A (shown with opened access cover to terminals).

Figure 2.20 - Bar primary CT

QUESTION

Why is it essential to know whether the phase sequence of the incoming shore supply is *'correct'*?

ANSWER

By *'correct'* we mean that it is the *same* sequence as the ship's supply (red-yellow-blue). A reversed phase sequence (red-blue-yellow) will produce a *reversed* shaft rotation in all three-phase motors because the direction of their rotating magnetic fields will be reversed, with disastrous results.

This fault is remedied by interchanging any two conductors of the shore supply cable at the connection box.

2.7 Shore Supply Connection

A shore supply is required so that the ship's generators and their prime movers can be shut down for major overhaul during a dry docking period.

There must be a suitable connection box conveniently located to accept the shore supply cable. The connection box is often located at the entrance to the accommodation or in the emergency generator room. The connection box must have suitable terminals to accept the shore supply cable, including an earthing terminal to earth the ship's hull to the shore earth.

The connection box must have a circuit breaker or an isolator switch and fuses to protect the cable linking the connection box to the main switchboard, with a data plate giving details of the ship's electrical system (voltage and frequency) and showing the method for connecting the shore supply cable.

A voltmeter and a phase-sequence indicator (PSI) are fitted to indicate shore supply voltage and correct supply phase sequence.

A phase-sequence indicator may incorporate either two lamps for 'right' (R-S-T) and 'wrong' (R-T-S) phase-sequence monitoring or a rotary pointer driven by an integrated small three-phase motor.

At the main switchboard, an indicator is provided (usually a lamp) to indicate that the shore supply is available for connection to the busbars via a connecting switch or circuit breaker. In general, it is impossible to parallel the shore supply with the ship's generators. The ship's generators must, therefore, be disconnected before the shore supply can be connected to the main switchboard.

Normally, the shore switch on the main switchboard is electrically interlocked with the generator's circuit breakers, so that it cannot be closed until the generators are disconnected from the ship's mains (as this will cause a brief mains blackout before shore power is applied).

Figure 2.21 shows a typical shore connection arrangement, but some variations occur.

The shore supply may have a different frequency and/or voltage to that of the ship's system.

- A higher frequency will cause motors to run faster, be overloaded and overheat
- a higher voltage will generally cause equipment to take excess current and overheat. It will also cause motors to accelerate more rapidly and this may overstress the driven loads
- a lower voltage is generally not so serious but may cause motors to run slower and overheat, or to stall.

Figure 2.21a - Ship's shore connection board

Figure 2.21b - Shore-based connection board

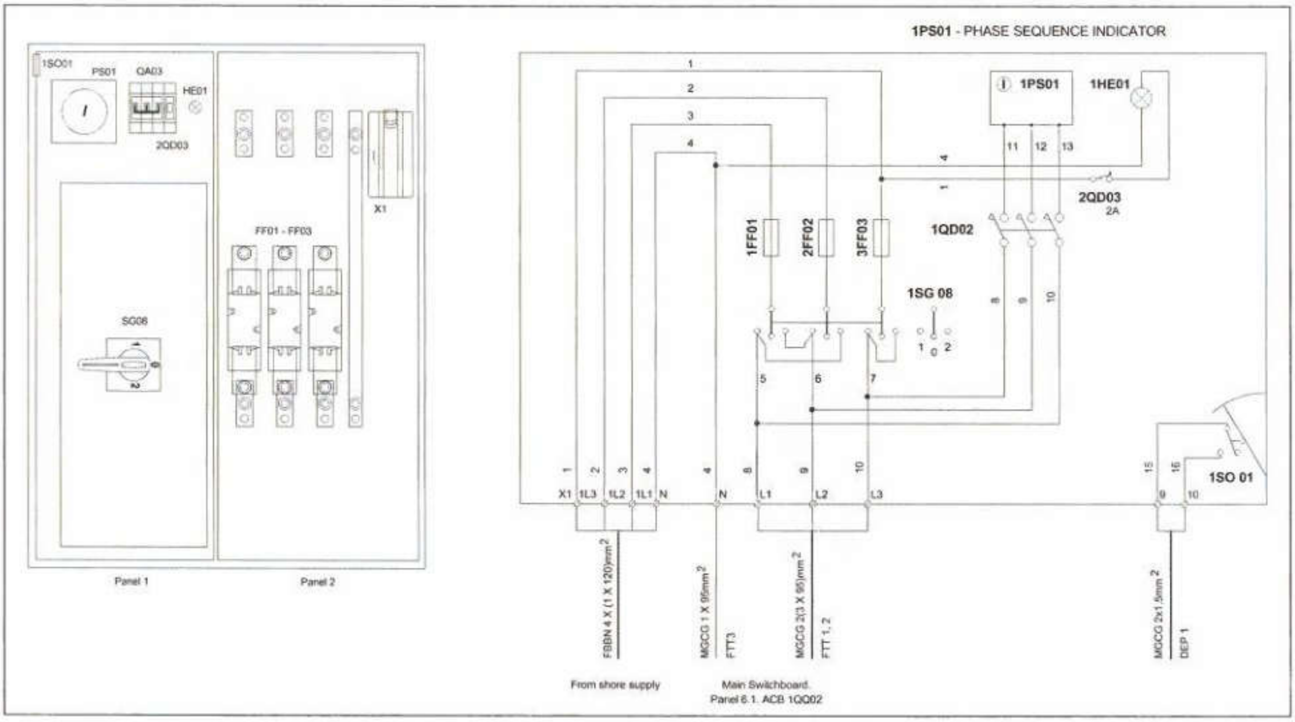


Figure 2.21c - Ship/shore connection board

QUESTION

If your ship is designed for 60 Hz at 440 V – what value should the shore supply voltage be if operating at 50 Hz?

ANSWER

Supply voltage should be reduced to about 380 V.

If the shore supply frequency differs from the ship's normal frequency then, ideally, the shore supply voltage should differ in the same proportion.

Alternative Maritime Power Supply (AMP)

The risks of pollution and sustained environmental damage in ports all over the world are becoming an increasing issue. Over the last 15 years, increasing attention has been focused on reducing the pollution from the auxiliary diesel engines of ships that frequent, in ever increasing numbers, the ports and terminals around the world. These ships keep their auxiliary engines running when moored in port to ensure a continued power supply for essential services.

The European Parliament has adopted a directive, 2005/33EC, which requires consideration to be given to the measures that should be taken to reduce the contribution the combustion of marine fuels other than marine gas oil makes to acidification. Amongst other measures, it recommends shore connection capabilities in EU ports.

The US State of California also adopted a resolution to take preventive measures, called *'Airborne toxic control measure for auxiliary diesel engines on ocean-going vessels at berth in a California Port'* (93118.3, Title 17, Chapter 1, subchapter 7.5, California Code of Regulations). This section, calls for a reduction in emissions by limiting the time during which auxiliary diesel engines are operated on regulated vessels while docked at berth in a California port.

The IMO's Marine Environment Protection Committee (MEPC) agreed in July 2011 to a number of new regulations that were inserted into Annex VI of 'MARPOL' to deal with the greenhouse gases emitted from ships. The measures will affect all ships and require the issue of a new certificate called the International Energy Efficiency Certificate (IEEC). In addition, all new ships with a keel laying date on or after 1st July 2013 will also be required to meet the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP).

In accordance with these new regulations,

"In some ports shore power may be available for some ships, but this is generally aimed at improving air quality in the port area. If the shore based power source is carbon efficient, there may be a net efficiency benefit. Ships may consider using onshore power if available."

This means that each vessel brought into service in future should be fitted with a facility that allows brief parallel working of the ship's power plant with a shore power supply substation for taking over the power from shore and back while moored at the port.

Many port and ship operators in Denmark, Finland, Norway, Sweden, the UK, the USA, etc use shore-based electricity while moored in port.

Figure 2.22 - AMP – shore based

A few alternatives to this system are available. The first is to mount the cable management system on the ship or shore. The connection to shore is made via special HV cables to an integrated technical pit fitted into the quay. This application occupies a minimum of space and consists of the following components: electrical connectors (up to 12 kV), flexible cables, a slip ring assembly, an optical fibre accumulator, a motor reducer, a cable drum and an electrical control panel.

Figure 2.23 - AMP – ship based

Another alternative is to have a similar system fitted inside a standard-size container, which can be placed on the ship. As the whole system is inside a container, and therefore completely modular, it can remain in a fixed position on board for longer periods or, if necessary, can be moved on board another ship.

Such systems are becoming part of many ports' stationary and movable power network (barge mounted or vehicle-based).

Figure 2.24 - AMP – barge mounted

However, the rules regarding ship to shore power are becoming increasingly strict in some ports in California where, from 2015, vessels without shore connection capabilities may not berth (by 2015, 50% of the power used by ships must be electrical; by 2017 it must be 70% and by 2020 80%).

2.8 Circuit Protection

There are many forms of electrical protection available that are designed to protect the distribution system when a fault occurs. Protection relays are used to monitor overcurrent, over/under voltage, over/under frequency, earth leakage, unbalanced loading, overtemperature, reverse power (for generators), etc. The HV power system shown in Figure 2.25 lists typical protective relay functions.

As most protection relays monitor current and/or voltage, we will limit our examination to overcurrent and undervoltage protection, together with an appreciation of protective discrimination. (Reverse power protection is included with generator protection in Chapter 3.)

No matter how well designed and operated, there is always the possibility of faults developing on electrical equipment. Faults can develop due

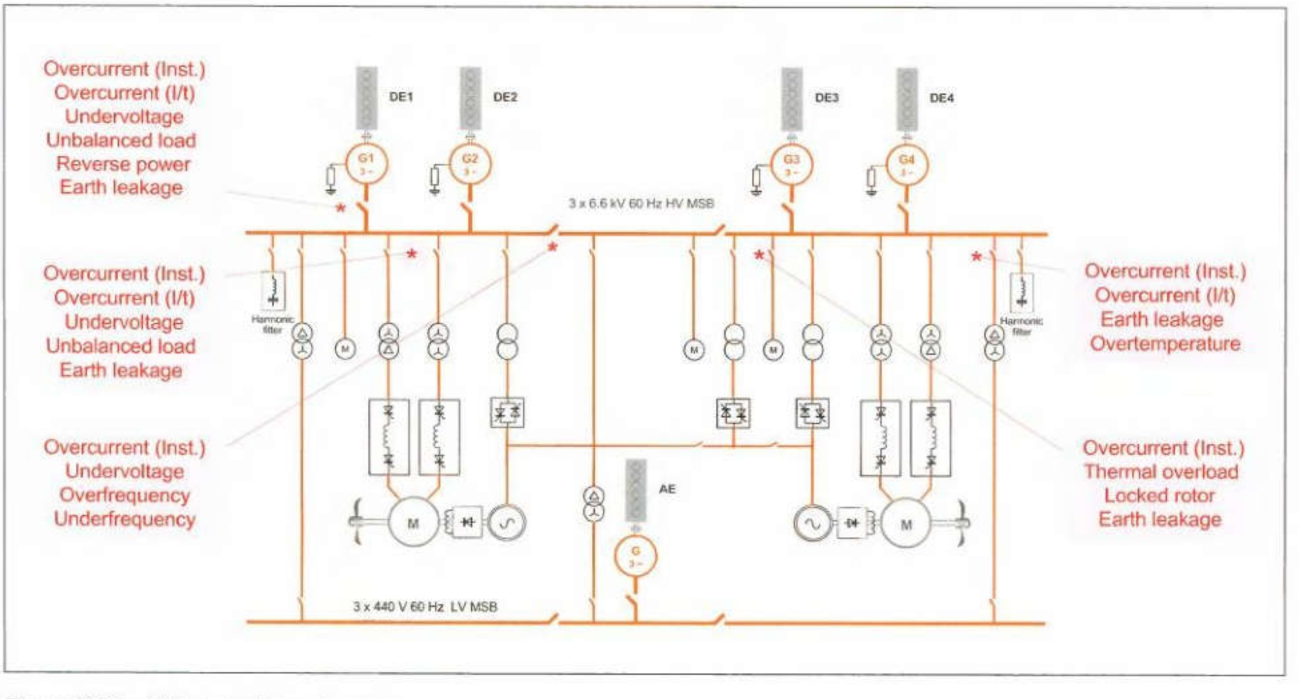


Figure 2.25 - HV protection scheme

to natural wear and tear, incorrect operation, accidental damage or neglect.

The breakdown of essential equipment may endanger the ship, but probably the most serious hazard is fire. Overcurrent (I^2R resistive heating effect) in cables and equipment will cause overheating and possibly fire.

The size of conductor used in cables and equipment is such that, with rated full load current flowing, the heat developed does not raise the temperature beyond about 80°C (ie 35°C rise above an ambient of 45°C).

A copper conductor can withstand very high temperatures (melts at 1083°C), but its insulation (generally organic materials such as cotton or plastic compounds) cannot withstand temperatures much in excess of 100°C. At higher temperatures, the insulation suffers irreversible chemical changes, loses its insulation properties and becomes burnt out. Short-circuit and overload currents must, therefore, be detected and rapidly cleared before damage occurs. (See Section 1.5.)

The protection scheme consists of circuit breakers, fuses, contactors, overcurrent and undervoltage relays. A circuit breaker, fuse or contactor interrupts the fault current. An overcurrent relay detects the fault current and initiates the trip action.

QUESTION

Suggest *three* reasons why protection equipment is essential in an electrical distribution system.

ANSWER

- To disconnect and isolate faulty equipment in order to maintain the power supply to the remaining healthy circuits in the system
- to prevent damage to equipment from the thermal and magnetic forces that occur during short-circuit and overload faults
- to protect personnel from electric shock.

The circuit breaker or fuse must be capable of safely and rapidly interrupting a short-circuit current. They must be mechanically strong enough to withstand the thermal and magnetic forces produced by the fault current. The size (strength) of the circuit breaker or fuse is specified by its breaking capacity, which is the maximum fault current it can safely interrupt.

For example, an MCCB may be continuously rated at 440 V with a rated current of 600 A. Its breaking capacity may be 12.5 MVA, which means it can safely interrupt a fault current of 16,400 A (from $12.5 \times 10^6/\sqrt{3} \times 440 = 16{,}400$ A).

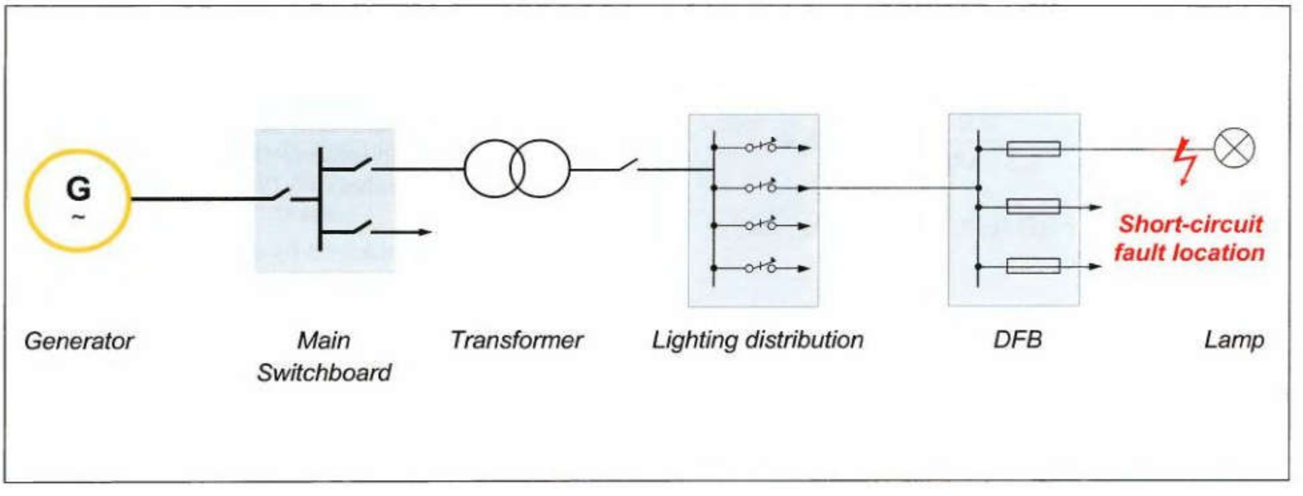


Figure 2.26 - Short-circuit fault location

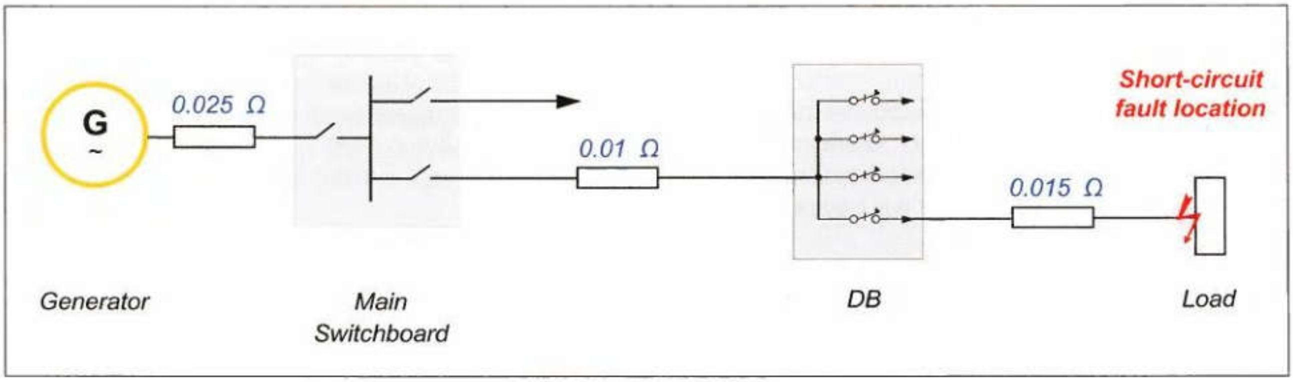


Figure 2.27 - Fault circuit

The prospective fault current level at a point in a circuit is the current that arises due to a short-circuit at that point (see Figure 2.26).

The size of this short-circuit fault current is determined by the total impedance of generators, cables and transformers in the circuit between the generator and the fault (see Figure 2.27). This total impedance is generally very small, so the maximum fault current (called the prospective fault current) can be very large.

A 440 V, 5 kW, 0.8 pf three-phase load is supplied as shown in Figure 2.27.

The normal full load power is

$P = \sqrt{3} \times V_L \times I_L \times \cos\varphi$ (W)

So, the load full load current is

$$I_L = \frac{P}{\sqrt{3} \times V_L \times \cos\varphi} = \frac{5{,}000}{\sqrt{3} \times 440 \times 0.8} = \mathbf{8.2\ A}$$

Suppose a short-circuit fault occurs at the load terminals.

The total impedance is:

$$Z_F = 0.025 + 0.01 + 0.015 = 0.05\ \Omega$$

and the prospective short-circuit fault current is:

$$I_F = \frac{V}{Z_F} = \frac{440\ V}{0.05\ \Omega} = \mathbf{8{,}800\ A}$$

So, the prospective fault current level at the load is **8,800 *A***

and, for a short-circuit at the DB, the fault level is:

$$\frac{440\ V}{(0.025 + 0.01)\ \Omega} = \mathbf{12{,}571\ A}$$

For a short-circuit at the main switchboard, the fault level is: $\frac{440\ V}{0.025\ \Omega} = \mathbf{17{,}600\ A}$

Note that the fault level increases the nearer the fault occurs to the generator.

The circuit breaker or fuse must have a breaking current capacity in excess of the prospective fault current level expected at the point at which it is fitted.

If it is less, the circuit breaker (or fuse) is liable to explode and cause fire.

The ability of a protection system to disconnect only the faulted circuits and to maintain the electrical supplies to healthy circuits is called protective discrimination.

Discrimination is achieved by coordinating the current ratings and time settings of the fuses and overcurrent relays used between the generator and the load, as shown in Figure 2.28. The protective devices nearest the load have the lowest current rating and the shortest operating time. Those nearest the generator have the highest current rating and the longest operating time.

If a short-circuit fault occurs in the lampholder in Figure 2.28, the fault current will be large enough to operate all protection devices from the generators to the fault. However, the 5 A fuse protecting the lamp circuit has the lowest current rating and shortest operating time in the system, so it will be the quickest to operate. This action will clear the fault and leave all other healthy circuits still connected.

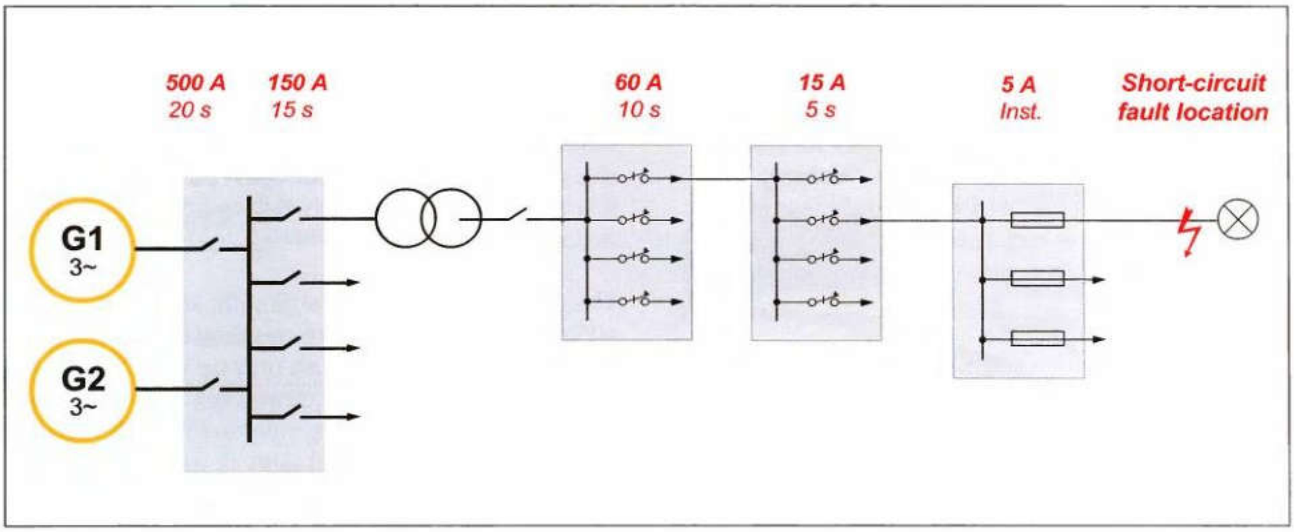


Figure 2.28 - Protective discrimination scheme

In the case of fuses, it is generally accepted that discrimination will be achieved if consecutive fuses have a ratio of about 2:1. The shipbuilder specifies the current ratings of fuses, together with the current and time settings of relays, in the protection scheme.

It is important that the original settings are maintained to achieve correct discrimination.

Overcurrent Protection

The general term 'overcurrent' applies to a relatively small increase over the full load current (FLC) rating (eg due to mechanical overloading of a motor), rather than the massive current increase caused by a short-circuit fault.

Generally, an overcurrent, supplied from a CT, is detected by a relay with an appropriate time delay to match the protected circuit.

Short-circuit faults in LV distribution circuits are mainly detected and cleared almost instantaneously by fuses, MCCBs and MCBs.

Main supply feeders are usually protected against short-circuits by circuit breakers with instantaneous magnetic trip action.

Overcurrent relay types:

- Magnetic
- thermal
- electronic.

All relay types have an inverse current time characteristic called OCIT (overcurrent inverse time), ie the bigger the current, the faster it will operate (see Figure 2.29). The basic inverse I/t curve would tend towards zero time for the highest currents. To make the relay action more precise at very high fault currents, the action is arranged to operate at a definite minimum time, which is fixed by the design. This type is called an OCIDMT (overcurrent inverse and definite minimum time) relay action. The OCIDMT can also be combined with an instantaneous (high set) trip to give the fastest action against extremely high currents caused by a short-circuit fault.

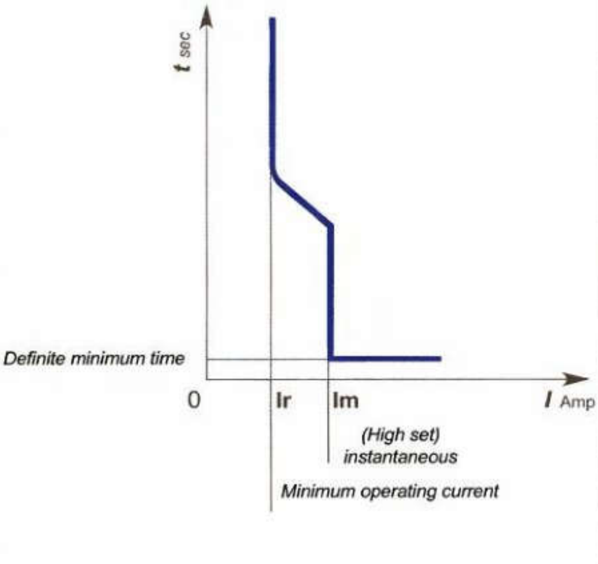


Figure 2.29 - Inverse current/time (I/t) curve

A magnetic relay, as shown in Figure 2.30, directly converts the current into an electromagnetic force to operate a trip switch. One type is the attracted armature action similar in construction to a simple signalling relay, but with an adjustment for the current setting. The time of operation is fixed at a definite minimum time, which is usually less than 0.2 seconds. This is regarded as instantaneous, ie with no deliberate time delay.

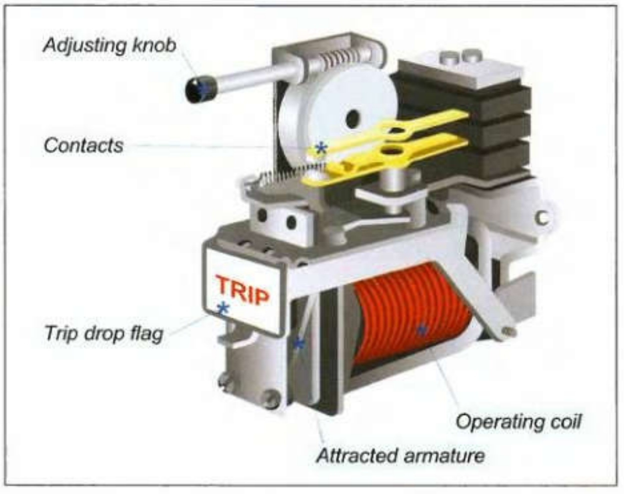


Figure 2.30 - Magnetic overcurrent relay (instantaneous action)

To obtain a magnetic inverse time action, eg for motor overload protection, an induction disc movement is usually employed. This construction is similar to a kWh energy meter used in a house but the disc movement is constrained by a spring so is not allowed to actually rotate. The disc travel is very small, but sufficient to operate a set of trip switch contacts. Both current and time settings are adjustable. A combined relay, including an attracted armature element and induction disc element, will give an instantaneous action (high set current) and an inverse/time characteristic.

Figure 2.31 shows a thermal relay that utilises the bending action of a bimetallic strip (one per each phase) to operate a set of incorporated contacts, which are in turn intended to trip a contactor or circuit breaker.

Full load current (FLC) will flow through the coil, wired in series with each phase of the load. This coil heats up the bimetallic strip, which is used as a trip lever.

In the event of overload, the current increases and heat radiated by the coil rises. This causes the bimetallic strip to bend, triggering the trip mechanism and the NC contact opens.

A mechanical bell-crank trip arrangement can also operate with unbalanced (differential) currents. This is particularly effective with a single phasing motor fault. In this case, two of the bimetal strips bend further in the normal direction with increased line current, while the other cools down allowing this strip to move relatively backwards (differential action).

The time taken to heat the bimetal strip to cause sufficient bending fixes the required time to trip. Resetting the relay can only be achieved after the strip has cooled down back to the ambient temperature. The inverse I/t overcurrent characteristic of a thermal relay is very useful for the indirect temperature protection of motors. Its thermal time delay is, however, far too long for a short-circuit fault so instantaneous protection must also be used in the form of fuses or a circuit breaker.

An electronic overcurrent relay usually converts the measured current into a proportional voltage. This is then compared with a set voltage level within the monitoring unit, which may be digital or analogue. In an analogue unit (as shown in Figure 2.32) the time delay is obtained by the time taken to charge up a capacitor. This type of relay has separate adjustments for overcurrent and time settings, together with an instantaneous trip. The electronic amplifiers within the relay require a low voltage DC power supply, eg 24 V DC derived from a 220 V AC auxiliary supply.

Here, the input from a line current transformer (CT) is rectified to produce a DC voltage that is proportional to the line current. This voltage charges capacitor C2 at a rate set in conjunction with potentiometer R5, which determines the inverse time characteristic for the relay. When this capacitor voltage exceeds the predetermined level (set by R2), the detector circuit drives power transistor T1 to operate the output electromagnetic relay RLA, which switches trip and alarm contacts in the external circuits.

An instantaneous trip operation is obtained by applying the output of the bridge rectifier directly to the input of the amplifier with a voltage set by R4. Therefore, for higher values of fault current, the inverse-time delay circuit is bypassed.

Both the magnetic and electronic relays can be designed to give an almost instantaneous trip (typically less than 0.05 seconds or 50 ms) to clear a short-circuit fault.

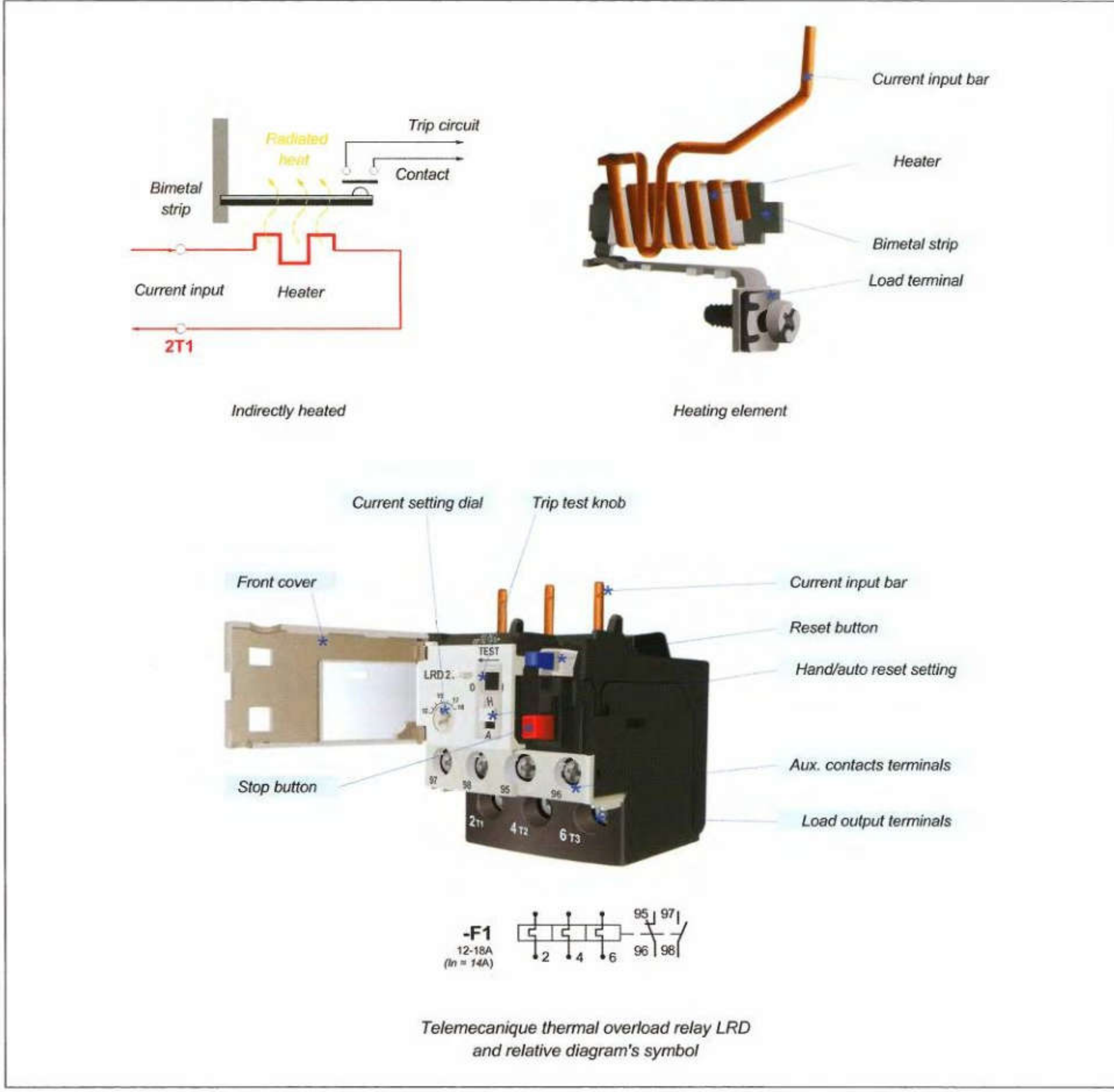


Figure 2.31 - Bimetallic thermal relay action

Thermal relays are commonly fitted in MCCBs and MCBs to give a 'long time' thermal overcurrent trip in addition to a magnetic action for an instantaneous trip with a short-circuit fault.

Overcurrent protection relays in large power circuits are generally driven by current transformers (CTs).

The CT secondary usually has a 5 A or 1 A rating for full load current in its primary winding.

All overcurrent relays can be tested by injecting calibrated test currents into them to check their current trip levels and time delay settings.

Primary injection is where a calibrated test current is fed through the normal load circuit. This requires a large current injection test set. The test set is a transformer and controller, rather like a welding set, ie it gives a low voltage – high current output.

Small secondary injection currents (5-50 A) are fed current directly into the overcurrent relay, usually via a special test plug/socket wired into the relay. Secondary injection does not prove the CT performance (as it is disconnected during the test), but is the usual method for testing an overcurrent relay.

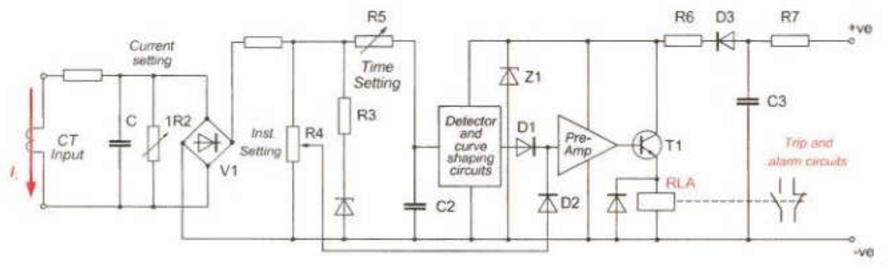


ABB electronic overload relay

Figure 2.32 - Electronic overcurrent relay circuit

The setting up of an overcurrent relay is critical to its protective duty so is carried out in strict accordance with the manufacturer's instructions.

Fuse Protection

A fuse is the most common type of protection against a short-circuit fault in LV distribution circuits, motor circuits and portable appliances. It is relatively simple, inexpensive and reliable. As re-wireable fuses tend to be less reliable than the cartridge type and are open to abuse (fitting the wrong size of fuse wire), they are not recommended for marine practice. HRC (high rupturing capacity – eg 80 kA) cartridge-type fuse links are normally used. A typical construction is shown in Figure 2.33.

A disadvantage of a fuse is its insensitivity to small overcurrents. An HRC fuse will blow at currents as low as 25% overload, but only after about 4 hours.

The advantage of a fuse is its very high speed of operation (a few milliseconds) at high short-circuit fault current – faster than a circuit breaker.

Fuses are fitted in circuits to provide protection against short-circuits. Protection against relatively small overcurrents (eg due to shaft overloading on a motor) is provided, where necessary, by an overcurrent relay (OCR).

A starter overcurrent relay protects the motor against relatively small overcurrents. The fuse links provide backup protection for the supply cables and generators against a short-circuit fault.

Motor fuses are typically rated at 2-3 times the motor full load current to withstand the large starting current surge (up to 5-7 times full load) of the motor. The motor manufacturer will specify the correct rating of fuse link for a particular motor rating.

Important points to note about fuses:

- In the event of a fuse blowing, the cause of the fault must be located and repaired before the fuse link is replaced
- the replacement fuse link must be of the correct current rating, grade and type. Usually this means the replacement fuse link is identical to the blown fuse link
- replace all three fuses in a three-phase supply, even if only one is found blown after a fault. The others may be seriously weakened, which makes them unreliable for future use.

The reference symbols used on an HRC fuse link include the current rating, voltage, application (eg motor, transformer, diode, general use), physical size and type of fixing arrangement.

Undervoltage Protection

An undervoltage release mechanism (UVR) is fitted to all generator breakers and some main feeder circuit breakers. Its main function is to trip the breaker when a severe voltage dip (around 50%) occurs.

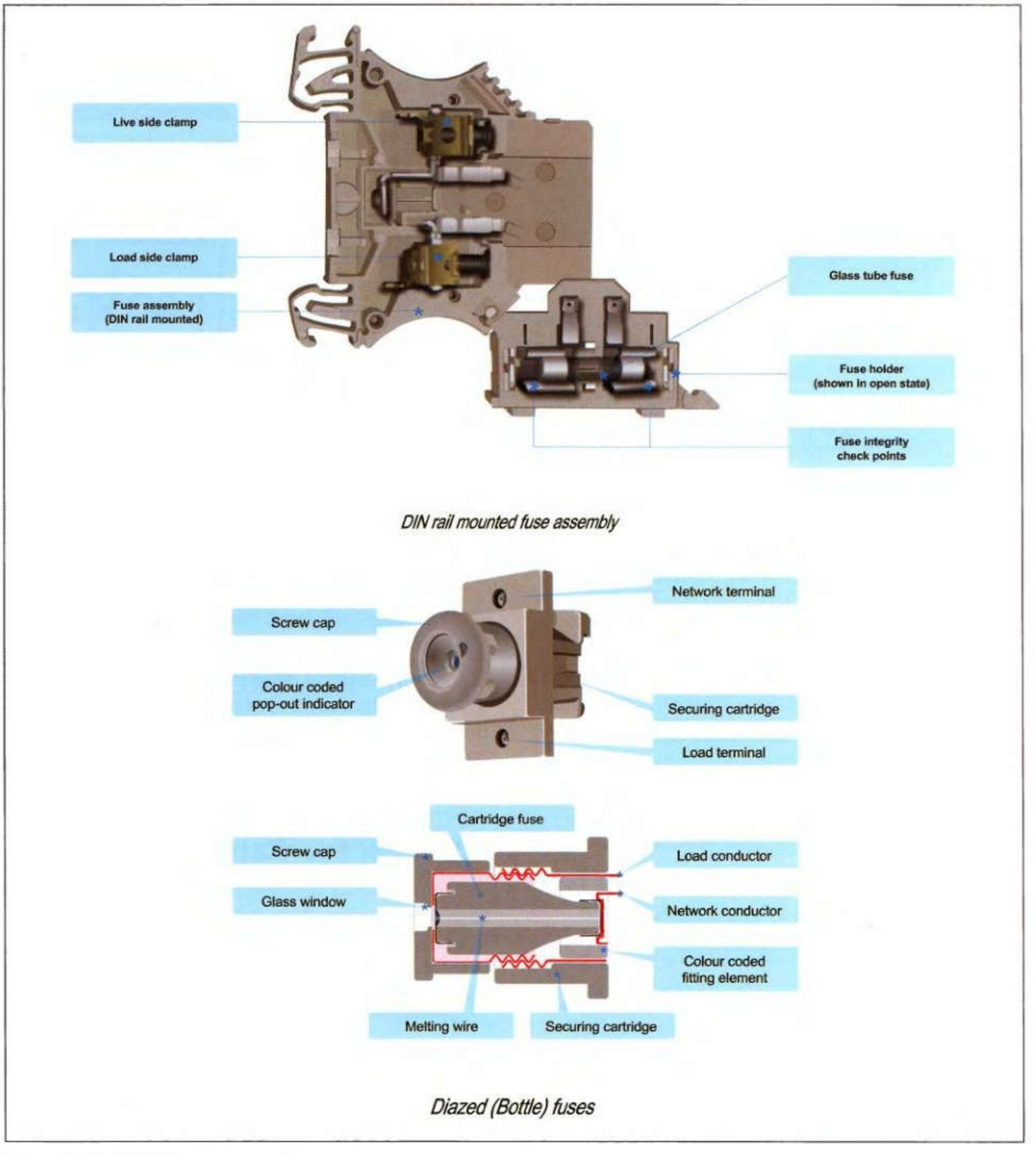
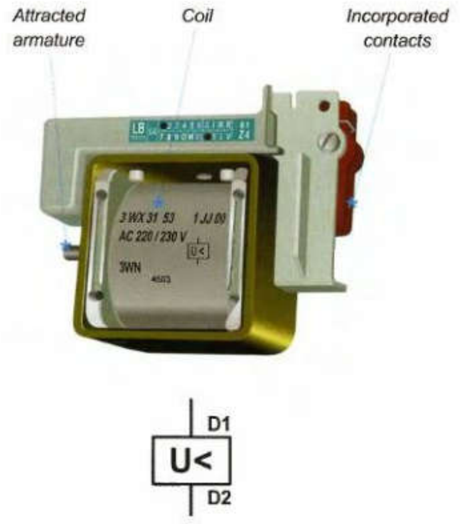


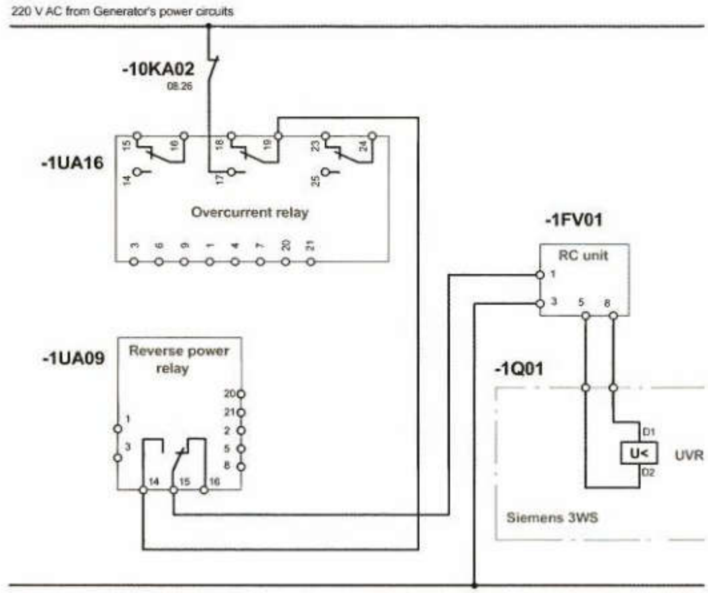
Figure 2.33 - HRC fuse construction

This is achieved by releasing the mechanical latch (which keeps the main contacts closed) to trigger the trip mechanism that opens the breaker main contacts and disconnects the load from the power source. The UVR on a generator circuit breaker prevents it being closed when the generator voltage is very low or absent, and therefore prevents closure of the dead generator's circuit breaker.

As shown in Figure 2.34, an undervoltage release, powered via the safety circuits of the generator and incorporated into the generator's circuit breaker, also provides overload and reverse power protection.



Siemens ACB 3WS Undervoltage release for generators' circuit breakers.



Siemens ACB 3WS Undervoltage release connection diagram.

Figure 2.34 - Undervoltage protection

QUESTION

A three-phase short-circuit occurs on the main busbars and the short-circuit trip of the running generator breaker fails to operate. Explain how the undervoltage relay provides a *backup* trip.

ANSWER

The short-circuit reduces the busbar voltage to zero, which causes the U/V release to trip the breaker.

Undervoltage protection is also required for motor starters. The starter contactor normally provides this protection as it drops out when the supply voltage is lost or is drastically reduced. The starter circuit will not normally allow the motor to restart when the voltage supply is restored, except when special automatic restarting facilities are provided.

Checking and calibration of generator undervoltage releases can only be carried out accurately by calibrated voltage injection. A known variable voltage is directly applied across the undervoltage release terminals to check:

- The voltage at which the UVRs coil pulls in
- the voltage at which it drops out.

A generator UVR is often off-delayed (by means of off-delay units), which prevents spurious tripping during transient voltage dips (typically 15%) caused by large motor starting currents.

2.9 Electric Cables

Ship wiring cables have to withstand a wide variety of environmental conditions. Improved materials have led to ship wiring cables of a fairly standard design that are safe, durable and efficient under all conditions.

The normal distribution voltage on ships is 440 V and cables for use at this voltage are designated 600/1000 V, ie 600 V to earth or 1000 V between conductors.

Higher voltage systems require cables with appropriate ratings, eg for a 3.3 kV three-phase earthed neutral system, the required cable rating is 1900/3300 V. For three-phase insulated systems, the cable rating would be 3300/3300 V.

Cable conductors are of annealed stranded copper, which may be circular or shaped. Cables with shaped conductors and cores are usually smaller and lighter than cables with circular cores.

Cable insulation has a thickness appropriate to the system voltage rating. Insulation materials are generally organic plastic compounds. Butyl rubber, which is tough and resilient, has good heat, ozone and moisture resistance. However, it has now been largely superseded by ethylene propylene rubber (EPR) insulation. EPR has similar electrical and physical properties to butyl rubber but with better resistance to moisture and ozone. It should not, however, be exposed to oils and greases.

Cross-linked polyethylene (XLPE), as shown in Figure 2.35, is also used as an insulant but has inferior mechanical and thermal properties when compared with EPR. Polyvinyl chloride (PVC) is not generally used for ships' cables, even though it is very common ashore. PVC tends to soften and flow at high temperatures (melts at 150°C), and hardens and cracks at low temperatures (–8°C). Even at normal temperatures, PVC tends to flow and become distorted under mechanical stress – for example, necking occurs at cable glands, causing the gland to lose its watertight properties.

Multicore shipwiring cables have the cores identified by either colour, printed numerals on untaped cores or numbered tapes on taped cores.

QUESTION

What is the purpose of the *sheath* on a cable?

ANSWER

The *sheath* of a cable protects the insulation from damage – it is not classed as an insulant. Sheath materials are required to be heat, oil and chemical resistant and flame retardant (HOFR). The sheath must also be tough and flexible.

Polychloroprene (PCP or neoprene) is a common sheath material but has been largely superseded by chlorosulphonated polyethylene (CSP or hypalon). CSP-HOFR sheathing compound is well suited to shipboard conditions. It offers good resistance to cuts and abrasions, resists weather, ozone, acid fumes and alkalis, and is flexible.

Extra mechanical protection is provided by armouring with basket-woven wire braid of either galvanised steel or tinned phosphor bronze. The non-magnetic properties of phosphor bronze are preferred for single core cables. A protective outer sheath of CSP compound covers the wire braid. The wire braiding also acts as a screen to reduce interference (caused by magnetic fields) in adjacent communication and instrumentation circuits.

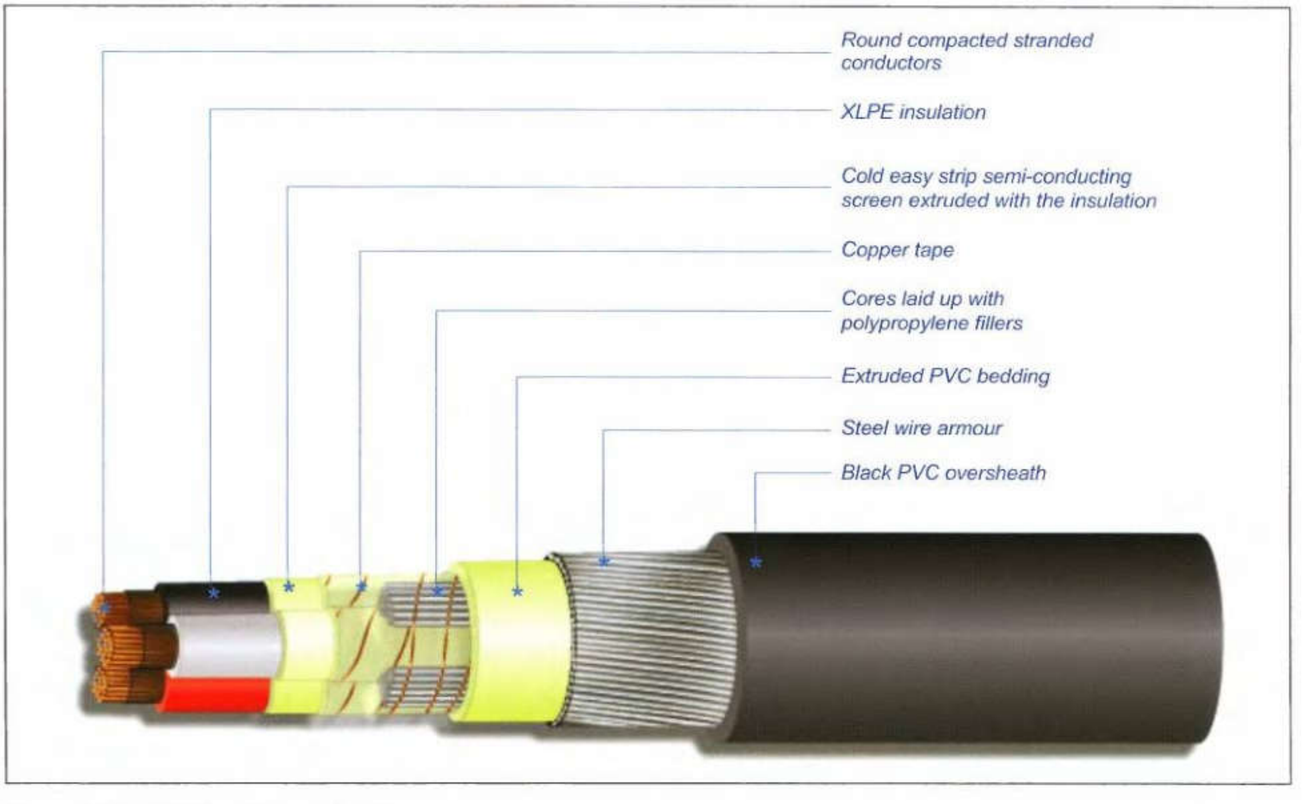


Figure 2.35 - XLPE cable construction

QUESTION

Will cable materials burn?

ANSWER

Yes. All organic materials will eventually burn in a severe fire. Cable sheath materials commonly in use are organic plastic compounds that are classed as flame retardant, ie will not *sustain* a fire. Most cable materials now achieve this property by developing chlorine gas and acid fumes to smother the flame.

PVC is notorious for its release of deadly acid fumes, but PCP and CSP do the same. EPR and XLPE do not. Some newer materials do not produce acid fumes when burning – an important feature for fire-fighting personnel. However, burning cable materials still tend to produce dense black smoke.

MIMS Cables

Mineral insulated, metal sheathed cables (MIMS) are very useful in high temperature, fire-risk areas. These cables have a magnesium oxide powder as insulation with a metal sheath, usually copper (MICC – mineral insulated, copper covered), which is covered with PVC for weatherproofing. A special termination is used with MIMS cables to provide a moisture-proof seal for the hygroscopic insulation powder. For an MICC cable, this is achieved by a compound-filled brass pot screwed directly on to the copper sheath, as shown in Figure 2.36.

The current rating of a cable is the current the cable can carry continuously without the conductor exceeding 80°C with an ambient air temperature of 45°C (ie a 35°C rise). This rating must be reduced (de-rated) if the ambient temperature exceeds 45°C or when cables are bunched together or enclosed in a pipe or trunking, which reduces cooling. MICC cable current ratings are based upon a copper sheath temperature of 150°C maximum.

For all types of cable, the size of conductors required for a particular installation is estimated from current rating tables issued by suppliers. These tables show current ratings for a range of cable types, conductor area and volt-drop/amp/metre.

The volt drop in cables from the main switchboard to the appliance must not exceed 6% (in practice it is about 2%). The cables installed must comply with both the current rating and the volt-drop limitation. Cable volt-drop only becomes a problem in very long cables.

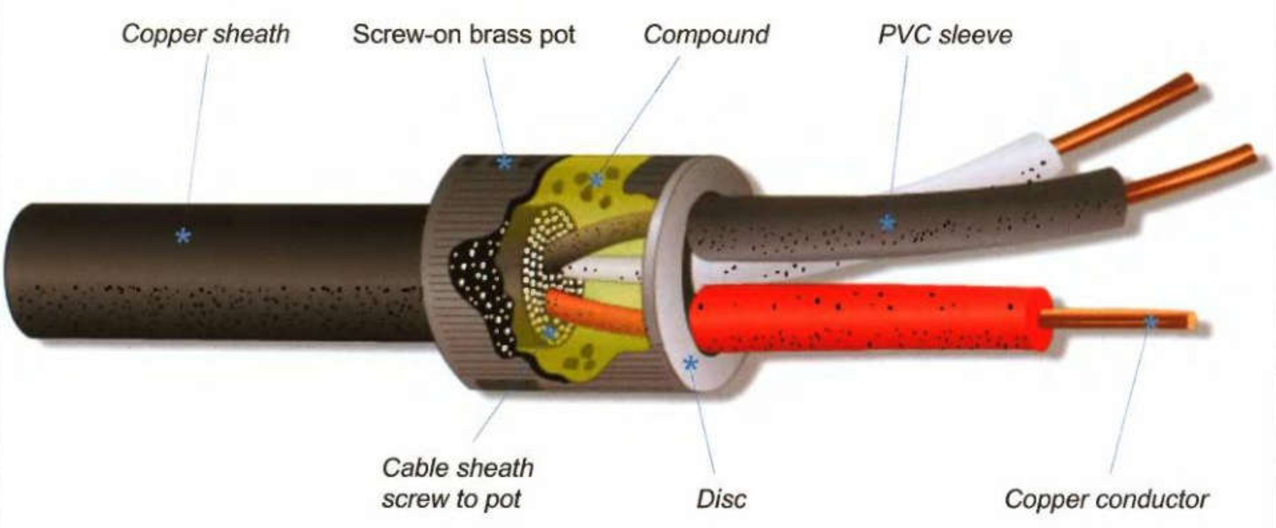


Figure 2.36 - MICC cable termination

QUESTION

What is the purpose of a cable gland?

ANSWER

Cables are insulated, mechanically protected and watertight. They may be armoured and suitable for installation in a hazardous explosive area. A cable gland maintains these properties where the cable is terminated at an appliance, eg at a motor terminal box.

The cable gland is screwed into the appliance terminal box. Nuts on the gland compress sealing rings to maintain watertight seals on the inner and outer sheaths and to clamp the armour braiding. The gland must be matched to the size and type of cable. A typical Ex-protected gland construction (which is more complicated than an equivalent industrial type) is shown in Figure 2.37.

In most cases, earthing of the cable armouring is by the cable gland. Where cables pass through watertight bulkheads and fire-stop barriers, they must be specially glanded to maintain the integrity of such bulkheads.

Conductor termination sockets can be soldered to the conductors but are more frequently crimped onto each wire by a compression tool.

Cable sockets must be securely attached to the appliance terminal screw by nuts and shakeproof washers. A loose terminal will invariably become a source of localised overheating. Periodic maintenance should always include checking the tightness of terminal connections. Small cables are terminated in terminal blocks.

Cables should be periodically inspected and tested, ideally when checking their connected appliances. Cable insulation resistance should be measured and the value recorded. Cables in exposed and damp situations, eg deck lighting, may develop a low insulation resistance. Usually this is a result of mechanical damage or a faulty gland permitting the ingress of water. Cables can be dried out by injecting a heating current from a current injection set or a welding transformer, as shown in Figure 2.38.

The procedure must be carried out carefully in order not to overheat the cables, which could cause further damage. The cable should be disconnected at both ends from equipment and connected as shown. The injection cables must have good connections at each end. Current flow and cable temperature should be carefully monitored. When satisfactory insulation values have been restored, a final check should be made with the cable at normal ambient temperature.

The injected heating current must never exceed the rated current for the cable – it is advisable to use an ammeter and to start at the lowest available setting on the injection set. The voltage should be in the region of 30 to 55 V depending upon the current setting. The cable temperature can be measured with a contact thermometer secured to

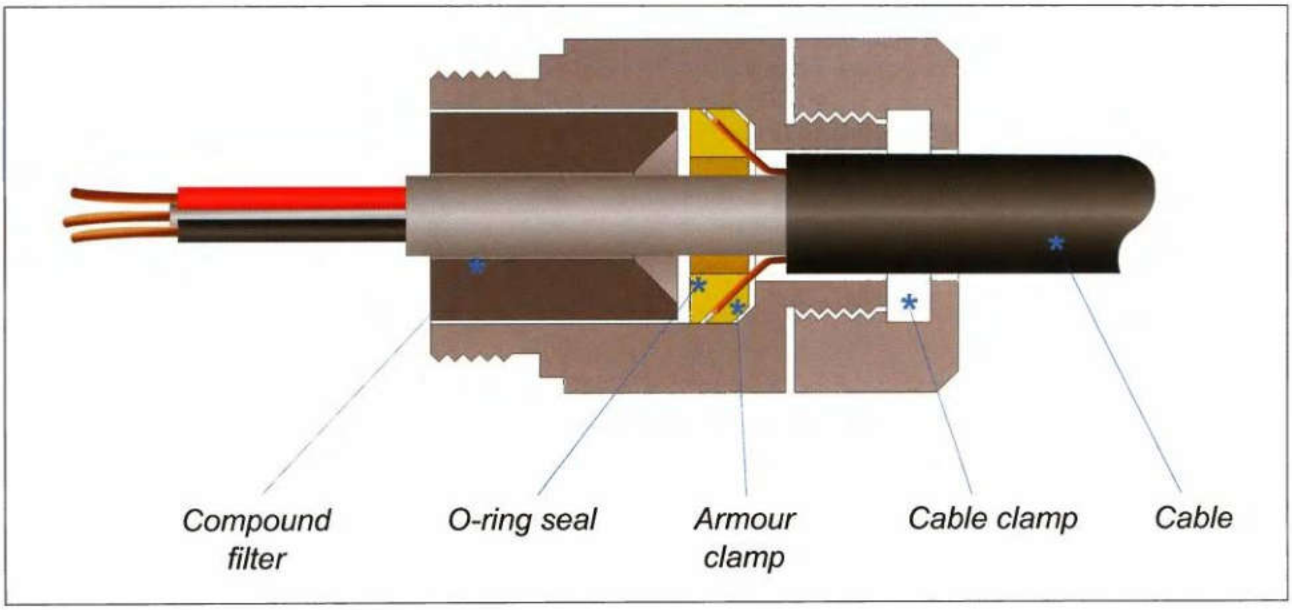


Figure 2.37 - Exd cable gland

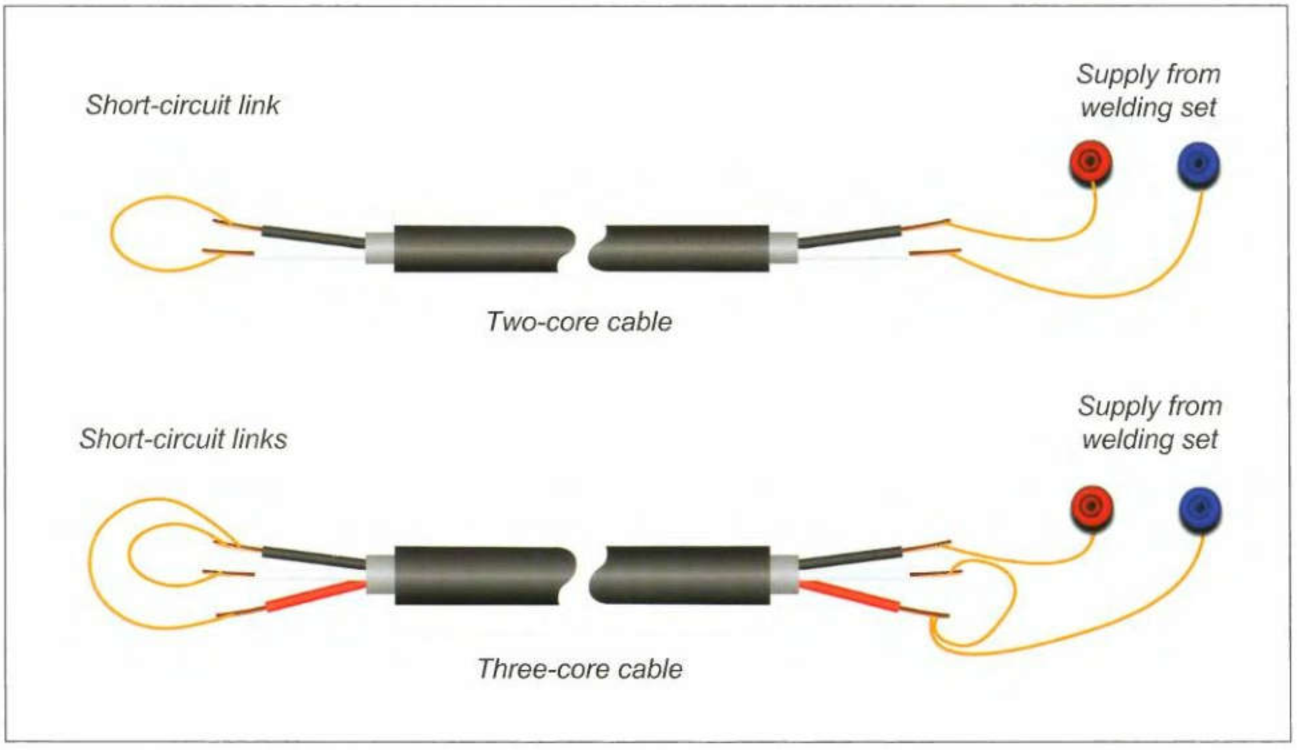


Figure 2.38 - Cable dry-out connections

the cable or with an infrared sensor and should not be allowed to exceed a temperature rise of 30°C. Temperature and insulation resistance should be measured and recorded every hour. When the insulation resistance becomes steady, heating should be carried out for a further four hours before switching off. Final readings of at least 20 MΩ to earth and 100 MΩ between cores should be expected.

Mechanical damage to cables must be made good either by repairing the damaged section with adhesive heat-shrink tubing or by replacing that section of cable. In the case of a partial cable replacement, adhesive heat-shrink tubing is also used for reconnection to an undamaged cable.

Unprotected metal armouring and insulation material are vulnerable to attack by moisture, chemicals and corrosive gases, while exposed live conductors are clearly dangerous. A temporary repair may be effected by preparing and binding the damaged section with a suitable adhesive plastic electrical insulating tape.

A temporary repair of this type will ***not*** be acceptable in a hazardous zone. Permanent cable repairs must be made as soon as possible.

Chapter Three
Generators and Main Circuit Breakers

The electrical power demand on board ship will vary according to the ship type and its day-to-day operational needs (at sea or in port). To meet the power demand, two or more main generators are used, which are backed up by an emergency generator and an emergency battery service.

The construction, operation, protection and maintenance of generators is described, together with a review of main circuit breakers and the main switchboard.

3.1 AC Generator Operation

Main generator power ratings range from, typically, 250 kW to 2 MW at 440 V, 60 Hz AC or 380 V, 50 Hz AC driven by diesel, steam turbine, gas turbine or propulsion shaft-driven prime movers. As the demand for increased electrical power installations arises (eg for specialist offshore vessels and cruise liners), it is necessary to generate at high voltage (HV) with voltages typically at 6.6 kV, 60 Hz but 3.3 kV and 11 kV are also used.

An emergency generator, typically 100 kW to 250 kW at 440 V or 220 V, will be diesel driven and fitted with an automatic start facility.

Note: The emergency generator can be used during lay time in port for the main power supply (either as a harbour generator in single mode or as a generator in parallel with one of the main generators). Therefore, the power ratings of emergency generators may be increased up to the power of the main generators while the ship is under construction.

The transitional source of emergency electrical power must be a storage battery which, in the event of failure of the main source of electrical power, will automatically and immediately come into operation to supply the emergency essential consumers (emergency lighting, general alarm, radio and navigation aids, the fire alarm system, etc). Its capacity must be sufficient to supply these essential consumers for a period of at least 30 minutes, during which time the battery voltage must remain within ± 12% of the rated voltage, without intermediate recharging. Battery supplies from lead-acid or alkaline cells are usually rated at 24 V DC.

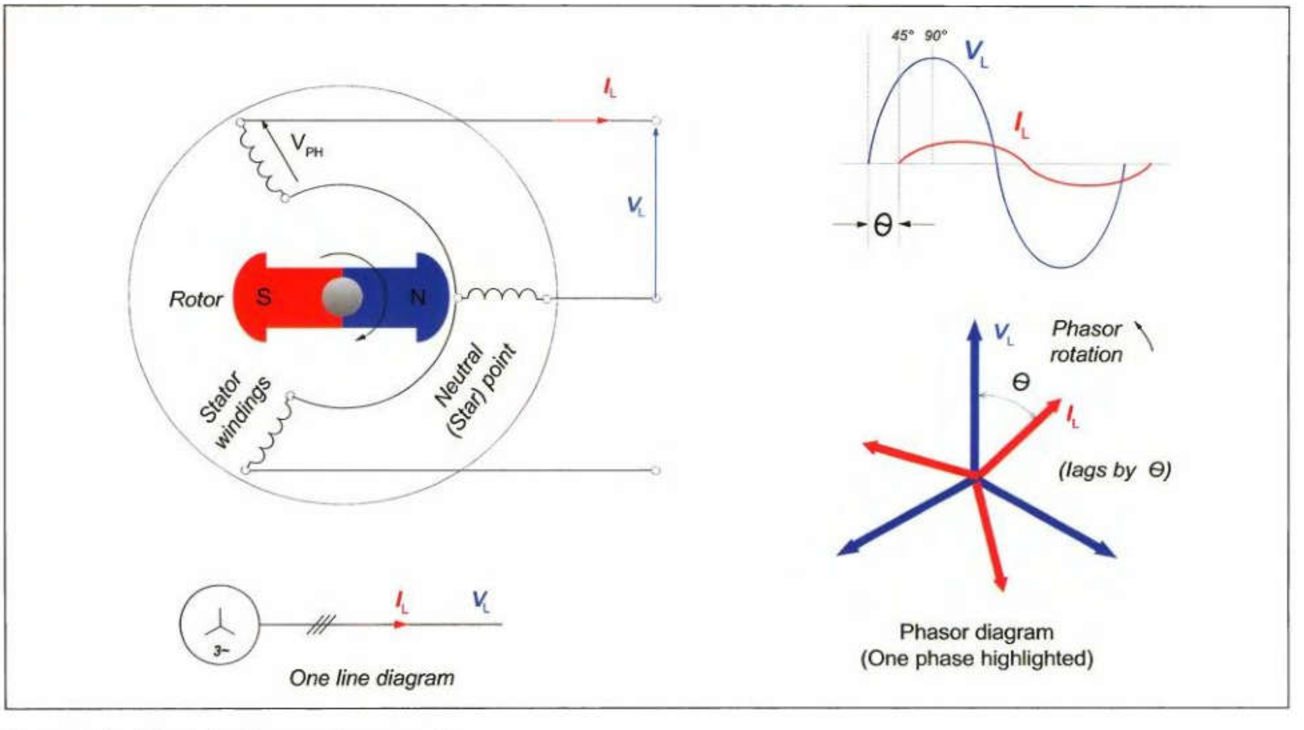


Figure 3.1 - Principle of generator operation

As the vast majority of ships use AC generators (sometimes called alternators), the principles and operational features will cover this type only.

The basic principle of an AC generator is very simple. Pairs of electromagnetic poles are driven (by the prime mover) past fixed coils of wire on the stator, as shown in Figure 3.1.

An alternating electromotive force (emf) which, ideally, has a sinusoidal waveform, is induced into each stator phase winding.

The useful emf level (*E*) is called the root mean square (*rms*) value and all equipment is rated in rms terms. A peak, or maximum, level is *1.414* ($\sqrt{2}$) times larger than the rms level,

eg if *E is 440 V*

then

$$E_{MAX} = 1.414 \times 440 = 622 \text{ volts.}$$

The size of emf generated depends on the strength of magnetic flux (Φ) and the rate at which this flux cuts the coils, so

$$\boldsymbol{E = n \times \varphi}$$

where *n* is the rotational speed of the rotor poles in rev/s.

The voltage available at the generator terminals is $V = E - (I \times Z)$ [*phasor calculation*] where *I* is the load current flowing in the stator phase windings. An internal phase volt-drop of ($I \times Z$) occurs due to the impedance *Z* of a phase winding, which is made up from its resistance and reactance.

The frequency *f* (measured in Hertz) of the emf is the number of waveform cycles per second. This depends on the rotational speed and the number of poles, so

$$f = n \times p$$

or

$$f = (N/60) \times p$$

where *n = speed in rev/s, N = rev/min* and *p = pairs of poles.* Related speeds and frequencies, with the number of pole pairs, are given in table 3.1.

Pole Pairs (p)	For 60 Hz rev/min (N)	For 50 Hz rev/min (N)
1	3600	3000
2	1800	1500
3	1200	1000
4	900	750

Table 3.1 - Speed and frequency for pole pairs

The two basic relationships for emf and frequency dictate how to control the voltage and frequency output of a generator. In practice, the speed is maintained practically constant by the generator's prime mover, which fixes the output frequency. The constant speed then allows the size of generated emf to be directly controlled by the size of pole flux (excitation).

An AC generator has three sets of coils, called phase windings, located in slots in the stator surrounding the rotating magnetic poles. The emf induced in each phase is 120° out of phase with the other two phases. Three-phase windings are labelled as U-V-W with colour coding of red, yellow and white used on terminals and busbars. One end of each of the three-phase windings is joined to form the neutral point of a star connection (often colour-coded in blue).

The other ends of the phase windings are connected to outgoing conductors called lines, which are coded as L1, L2 and L3.

The three output line voltages (represented by V_L) and the three output line currents (represented by I_L) combine to create the three-phase electrical power output of:

$$P = \sqrt{3} \times V_L \times I_L \times \cos\varphi \text{ (w)}$$

In a star connection, any line voltage V_L, is made up from two phase voltages, where

$$V_L = \sqrt{3} \times V_{PH}$$

The $\sqrt{3}$ factor is due to the 120° displacement between phase voltages. For example, if

$$V_L = 440 \text{ V}$$

then

$$V_{PH} = 254 \text{ V}$$

The rated values of a machine always refer to line conditions (as stated on the rating plate).

Angle φ is the phase angle between V_{PH} and I_{PH}, which is determined by the types of electrical load on the generator (eg lighting, motors, galley equipment etc).

Cosφ is the power factor of the electrical load and is typically about 0.8 lagging, which means that the current waveform lags about 37° behind the voltage.

Figure 3.2 - Power factor meter

QUESTION

The power factor meter shown in Figure 3.2 has its scale divided into *two* segments, each calibrated 0.6-1.0. What is the significance of each segment?

ANSWER

An indication in the upper half of the scale shows that the load is inductive (IND) or lagging. The lower half of the scale (with negative marks) indicates that the load is capacitive (CAP) or leading.

A three-phase AC generator rated at 500 kW, 440 V at 0.83 lag will deliver a full load line current of:

$$I_L = \frac{P}{\sqrt{3} \times V_L \times \cos\varphi}$$

$$= \frac{500{,}000}{\sqrt{3} \times 440 \times 0.83}$$

$$= \mathbf{790.5\ A}$$

This means that the phase windings, cable conductors and generator circuit breaker must be capable of carrying this full load current (FLC) continuously and without exceeding their temperature limits.

The speed of an auxiliary diesel-driven generator (DG) is accurately managed by an electronic governor that maintains an almost constant output frequency over its load range.

QUESTION

If the above 500 kW generator circuit breaker is protected by an overcurrent relay (OCR) setting of 125%, what will be the actual minimum tripping current level?

ANSWER

The full load line current is 790.5 A, so the generator overcurrent relay will trip at *125%*: *790 × 5 × 125/100* = **988 *A***

A propulsion shaft-driven (SG) generator can be an efficient method for extracting electric power from the ship's main engine as the power is derived from lower cost fuel than that used for an auxiliary DG unit. The SG may be fitted directly in-line with the slow speed propulsion shaft or, more commonly, be gear-driven up to a higher speed.

By using a shaft generator as the main source of electric power during long sea passages, the DG units operate for short periods only, which creates a reduced maintenance requirement.

An apparent disadvantage of a shaft generator is that it has no direct frequency control as this is determined by the main engine, which is set for the ship's full-away speed range (eg 70-100%). This means that the frequency must be separately regulated at the output of the shaft generator to maintain a constant 60 Hz to the ship's electric power consumers. Such a frequency regulator utilises an electric AC/DC/AC converter, as shown in Figure 3.3.

At the three-phase rectifier stage, the AC generator frequency is converted to a DC voltage. The three-phase controlled inverter converts the DC back to a fixed output frequency by sequenced thyristor switching. A DC link inductor coil is interposed between the rectifier and inverter to smooth the normal current flow and act as a current limiter in the event of a short-circuit fault.

An inverter thyristor switch is turned on by a positive current pulse to its gate when its anode is positive with respect to its cathode. The thyristor is only turned off when its current is reduced to (approximately) zero. This is a problem for the inverter thyristors when driving into the ship's inductive load (typically about 0.8 power factor lagging). In this case, the current continues to flow

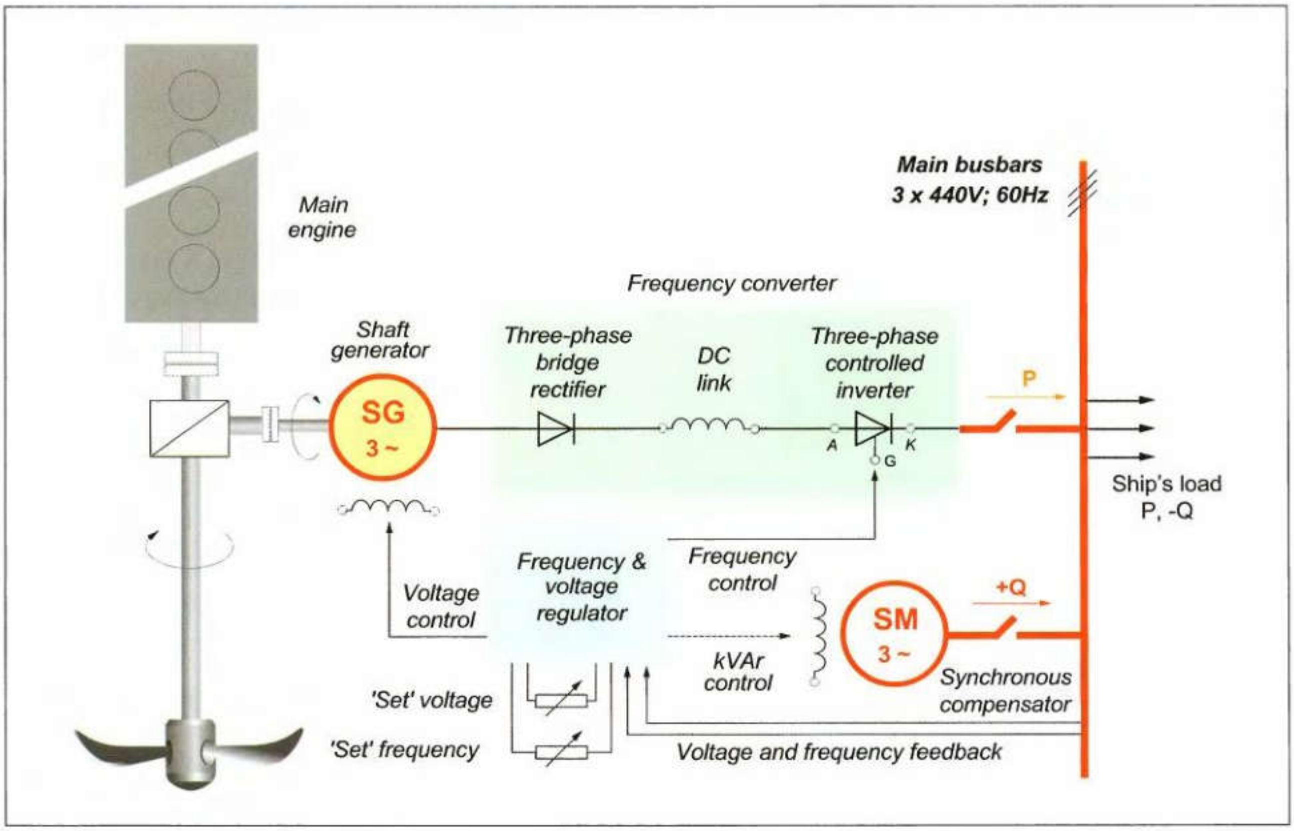


Figure 3.3 - Shaft-driven generator control

in a thyristor after its voltage has gone through a zero point, causing disruption of the inverter switching sequence.

To overcome this problem, it is necessary to have the thyristor current in phase with its voltage so that turn-off is automatically achieved (line commutation) at the end of each AC half cycle. The addition of leading kVAr compensation to the power system to create an overall unity power factor solves the problem. Therefore, the SG/ converter must only supply true power P (kW). At every instant, the leading kVAr (+ Q) must exactly match the lagging kVAr (– Q) of the ship's load, so the compensation must be automatically controlled. The practical solution is to include a synchronous motor, operating as a synchronous compensator, whose operating power factor is controlled by regulating its DC field current.

Overall, the busbar voltage is fixed by the field flux in the shaft generator and the busbar frequency is regulated by the controlled inverter.

3.2 Generator Construction and Cooling

3.2.1 Construction

The two main parts of any rotating AC machine are its stator and rotor.

The fabricated steel stator frame supports the stator core and its three-phase windings, as shown in Figure 3.4.

The stator core is assembled from laminated steel, with the windings housed in slots around the inner periphery of the cylindrical core.

The stator coils are interconnected (in the end-winding regions) to form three separate phase windings with six ends. These phase ends are found in the stator terminal box, as shown in Figure 3.5.

Occasionally, only three terminals are available in the terminal box and, if this is the case, the neutral or star point connection is an internal part of the stator winding arrangement.

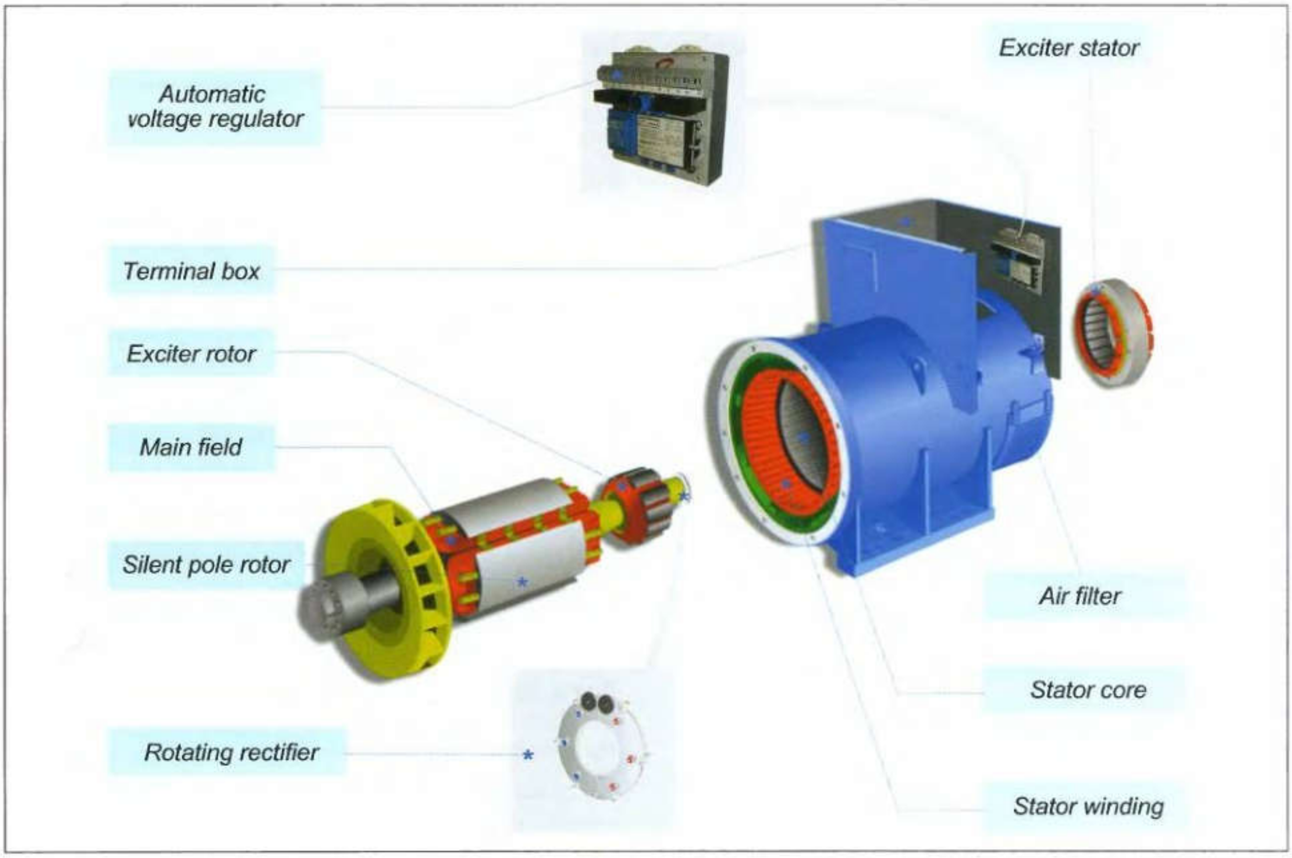


Figure 3.4 - Generator construction

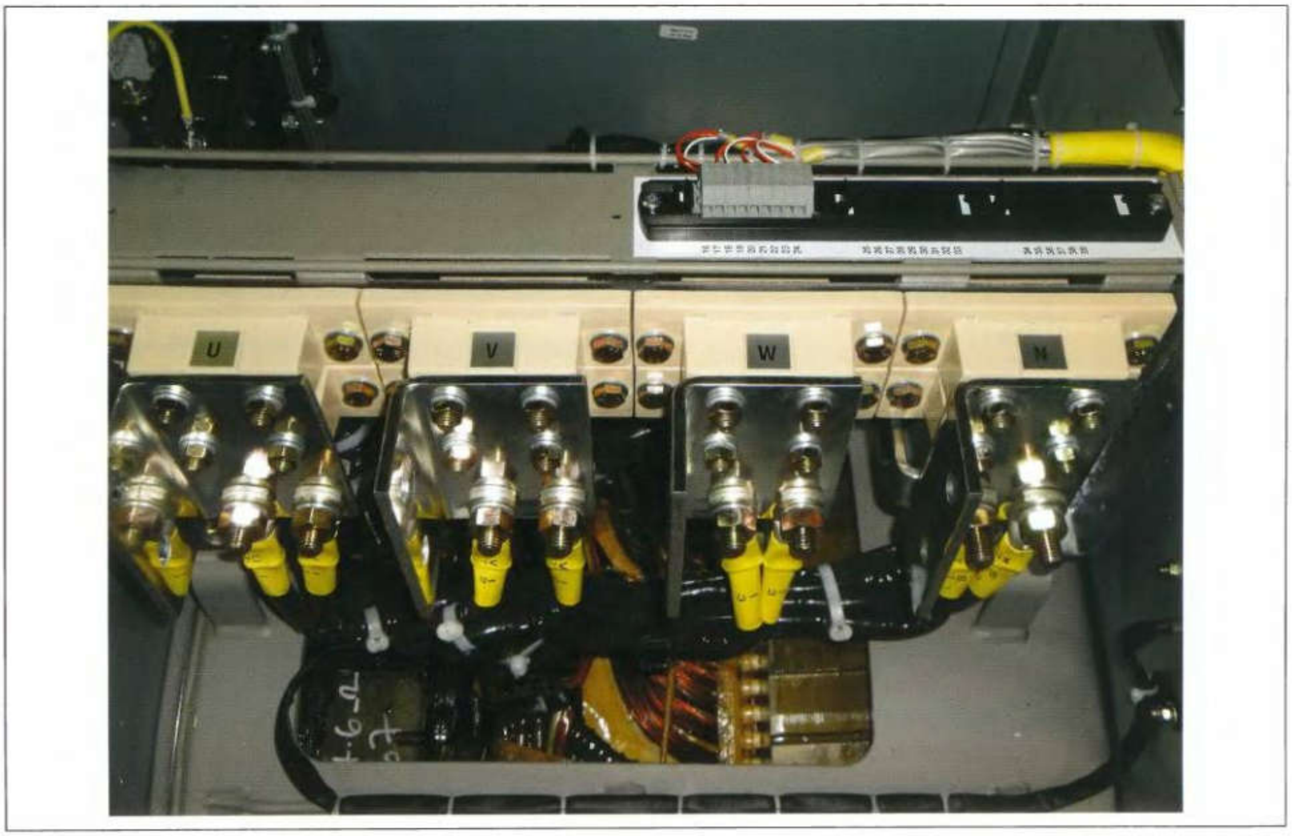


Figure 3.5 - Generator terminal box

The main outgoing cables connected to these terminals conduct the generator's electric power to its circuit breaker at the main switchboard.

The rotor of a main AC generator provides the field excitation from its electromagnetic poles. Two constructional forms of rotor are available, as shown in Figure 3.6.

Salient pole type

The salient pole type has projecting poles bolted or keyed onto the shaft hub. Field excitation windings are fitted around each pole. This type of rotor is used with medium and slow shaft speeds (1800 rpm and below) and is the most common arrangement for marine generators.

Cylindrical type

Cylindrical type rotors are generally used with large power, high speed (1500-3600 rpm) steam/gas turbine drives. The excitation windings are wedged into axial slots around the steel rotor. Unwound sections of the rotor form the pole faces between the winding slots.

The shaft bearings of large generators are usually insulated to prevent stray currents from circulating through. Unbalanced (stray) end-winding magnetic flux induces an emf along the steel shaft. This will cause a current to circulate through the shaft, bearings and bedplate to produce arcing across the bearing surfaces and degradation of the oil layer. Under unbalanced fault conditions, the bearing problem may be severe.

To prevent the flow of shaft current, one bearing (usually the non-drive end) is electrically isolated from earth by a thin layer of insulating material beneath the bearing pedestal. The pedestal holding down bolts must also be insulated by suitable sleeving.

In normal operation, the effectiveness of the pedestal insulation can be checked by measuring its voltage to earth, which may show as a few volts.

The rotor winding (main field) is supplied with DC from an exciter. If the exciter equipment is a conventional DC generator, or is static (see Section 3.3 on excitation methods), the DC excitation current is fed into the field windings via carbon brushes on a pair of shaft-mounted slip rings.

To eliminate the maintenance problems associated with rotating contacts, a brushless arrangement is usual for marine generators. All brush gear, commutators and slip ring assemblies are eliminated by using an AC exciter, with its output being rectified by a shaft-mounted rotating rectifier, as shown in Figure 3.7. The diodes are connected as a three-phase AC/DC bridge circuit.

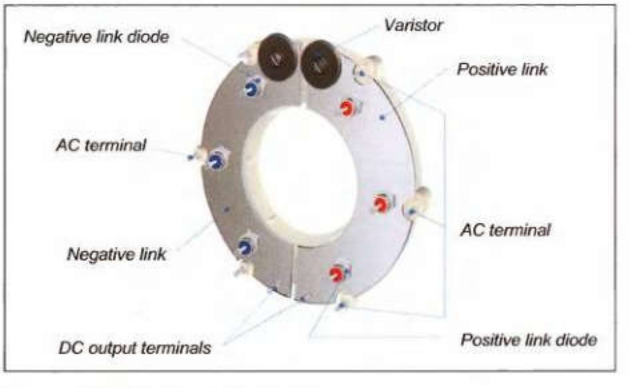


Figure 3.7 - Rotor diode plate

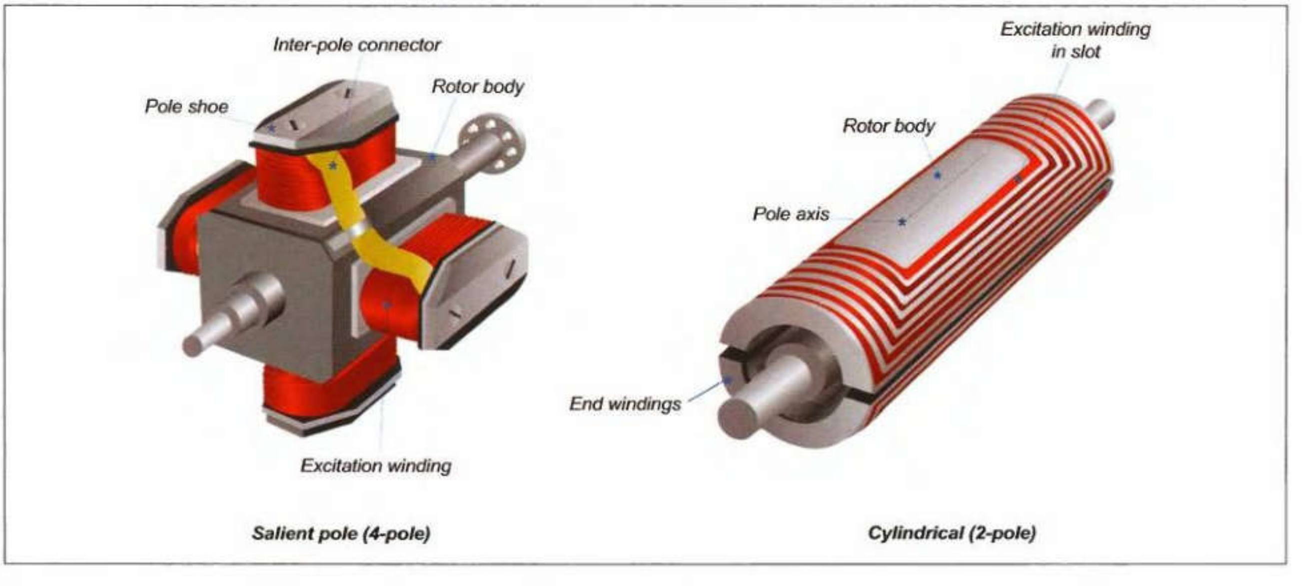


Figure 3.6 - Generator rotors, salient and cylindrical construction

The six diodes, mounted on the shaft, convert the AC exciter output to DC, which is then fed directly into the main generator rotor field windings.

The AC exciter has its own DC field poles fitted on its stator while the rotor carries its three-phase AC exciter output windings. This construction layout is inverted compared with that of the main generator.

3.2.2 Cooling

Power losses, typically 10% of the generator rating, cause internal heating in the windings and magnetic cores of both the rotor and the stator. This heat must be continuously transferred out of the generator to prevent excessive temperature rise causing breakdown of the winding insulation.

Forced air circulation in a closed circuit (to prevent ingress of dirt), via an air cooler, is pressurised by a fan on the rotor shaft.

Cooling air is forced through ventilation ducts in the stator core, between rotor poles and through the air gap (a few millimetres) between the stator and rotor.

Water cooling of the circulating air may also be used for generators with a large power rating. Temperature detectors (often RTDs such as Pt 100) are used to monitor the temperature of stator windings, bearings and the cooling air/water of the generator. Single or grouped temperature alarms are activated at the main watchkeeping position.

While the generator is stopped during standby or maintenance periods, low power electric heaters within the machine prevent internal condensation forming on the winding insulation. These heaters may be switched on manually or automatically from auxiliary contacts on the generator circuit breaker.

Heater power supplies are normally 220 V AC single-phase, supplied from a distribution box local to the generator.

3.3 Excitation Methods

The two factors essential for the production of a generated emf in an AC generator are rotational speed (n) and magnetic flux (Φ). Field windings on the rotor create strong magnetic field poles when direct current is passed through them. Various methods have been devised to supply the correct DC field (excitation) current to produce the required AC output voltage from the stator terminals. The excitation must be continually regulated to maintain the generator output voltage as the load power demand fluctuates.

Excitation methods are either rotary or static. A rotary method utilises an exciter, which is shaft-mounted and rotates with the main generator rotor. The most common arrangement is to use a shaft-mounted AC exciter.

In some applications, a small additional rotary pilot exciter may be used to supply current to the main exciter field. A pilot exciter is a small permanent magnet AC generator that is driven from the generator shaft. Its output voltage is generally at a high frequency (eg 1000 Hz) but this is changed to DC before being fed into the main exciter field.

A brushless excitation scheme is shown in Figure 3.8. The absence of brushes, brushgear and carbon dust improves reliability and considerably reduces generator maintenance. Rectification of the AC exciter voltage is achieved by six shaft-mounted silicon diodes that form a three-phase rotating rectifier. The suppression varistor connected across the main generator field protects the diodes against voltage surges arising from sudden changes in excitation current.

QUESTION

The water cooling system on a large generator is out of service due to a faulty inlet valve. How will this affect the generator operation?

ANSWER

The generator can only be used to supply a much reduced electrical power output to keep the machine temperatures below their maximum permitted levels. External emergency doors in the generator's air cooling ducts may be opened in such cases. The penalty is that the normally closed air circuit of the generator is now open to the engine room atmosphere.

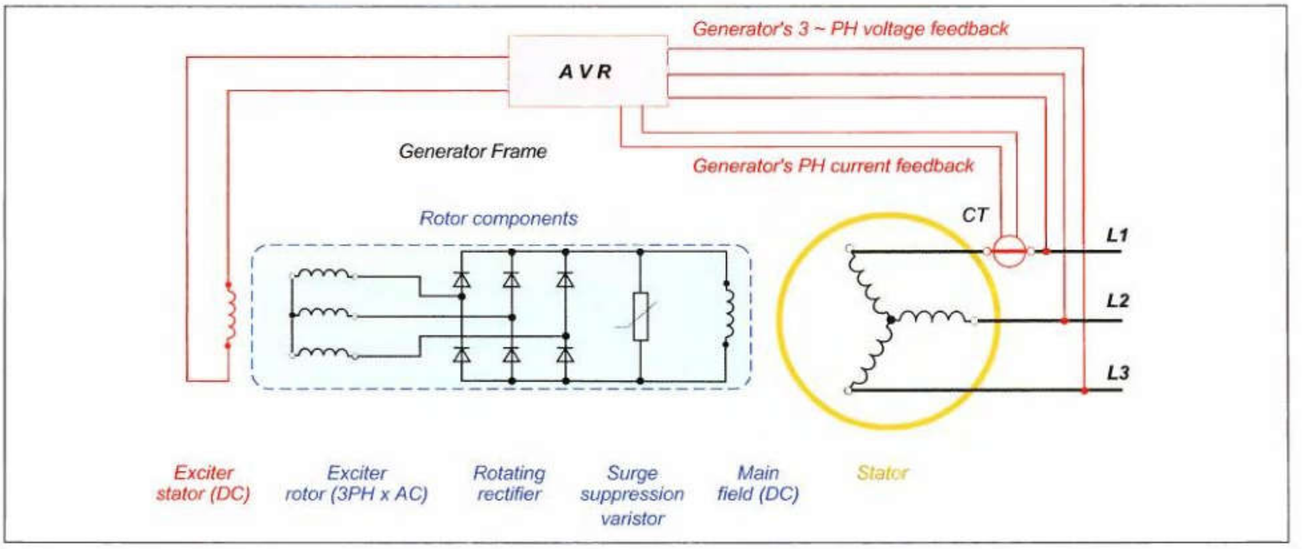


Figure 3.8 - Brushless excitation scheme

QUESTION

What is likely to happen if one of the rotating diodes fails and becomes:

(a) an open circuit?

(b) a short-circuit?

ANSWER

(a) The remaining healthy diodes would continue to supply the main field, although the total field current, and so generator voltage, will be slightly reduced. Under AVR control, the exciter field current would be automatically boosted to maintain the correct generator voltage, while the diode failure would probably be undetected. The exciter will gradually overheat.

(b) A short-circuited diode is more serious as it leads to a short-circuited exciter. Rapid overheating of the exciter will occur and the generator will lose excitation.

Although diode failures are rare, some generator field systems are fitted with an electronic detector relay to give an alarm and/or trip signal to the generator's circuit breaker should such a fault occur. Usually, the detector monitors the exciter field current, whose size and shape is noticeably affected by a diode failure.

Generators with rotary exciters, conventional or brushless, have a relatively sluggish response to sudden load changes. For example, it may take up to one second to correct a 15% voltage dip caused by the startup of a large pump motor.

QUESTION

What factors govern the overall voltage response of a generator to sudden (transient) load changes?

ANSWER

The main opposition to changes in the field current required to correct the generator output voltage are:

- Inductance of main rotor field winding
- inductance of exciter field winding
- automatic voltage regulator's response.

The transient voltage response of a generator can be improved by eliminating the rotary exciter in favour of a static excitation method. In this arrangement, the generator field draws its DC current via a static excitation transformer/rectifier unit fed directly from the generator voltage and current output. This arrangement is known as compounding as it is controlled by voltage (shunt effect) and current (series effect) feedback. Response times as low as 0.1 second to correct a 15% voltage dip are common with static excited compound generators. This fast response is desirable where heavy and frequent load surges arise from the deck machinery. However, despite advantages, this excitation method is utilised less frequently on board than the rotary method explained in the paragraph above.

Static excitation equipment may be located within the generator casing or inside the main switchboard. This type of generator has two shaft slip rings and brushgear to connect the static excitation equipment to the rotor field winding.

The basic scheme of a self-excited compounded generator is shown in Figure 3.9 (single-phase operation is shown for simplicity).

Note: *compounded* means that the excitation is derived from the generator output voltage and its current.

On no load, the generator excitation is provided by the PRI.1 winding of the excitation transformer. On load, the generator current injects an additional excitation current, via PRI.2 of the transformer, to maintain a constant output voltage. If the excitation components are carefully designed, the generator voltage of a compounded generator can be closely maintained at all loads without the use of an AVR or manual voltage trimmer. However, some generator manufacturers do include an AVR and a manual trimmer rheostat in such a compounded static excitation scheme. This addition may provide closer voltage regulation over the load range and allow manual control of the generator voltage, eg for synchronising and kVAr load balancing between generators.

A practical three-phase static excitation scheme has additional components, such as reactors and capacitors. The circuit in Figure 3.10 has no AVR or manual trimmer regulator. A load current surge will automatically feed back an adjustment to the field excitation to correct the resulting voltage surge so quickly that the output voltage remains practically constant.

Compound excitation systems require the static components to be designed to closely match its associated generator.

3.4 Automatic Voltage Regulation

Sudden load current surges (eg due to large motor starting) on a generator cause a corresponding change in its output voltage. This is due to an internal voltage drop in the generator windings and the effect is usually called voltage dip. Similarly, load shedding will produce an overvoltage at the busbars. An unregulated or non-compounded generator excitation system would not be realistic on board ship due to the varying voltage caused by the fluctuating load demand. Automatic voltage regulation (AVR) equipment is necessary to rapidly correct such voltage changes (see Figure 3.11).

An AVR will control the generator's voltage to ± 2.5% (or better) of its set value over the full load

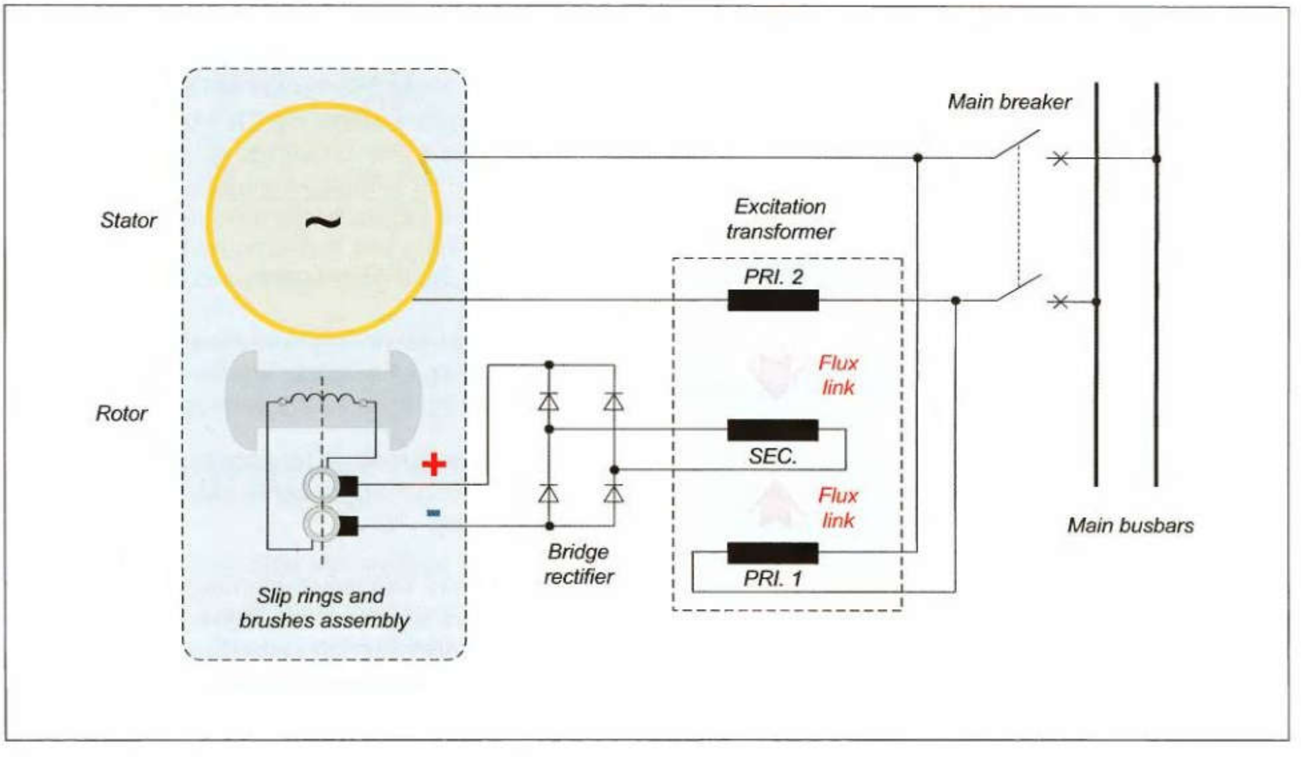


Figure 3.9 - Single-phase compound excitation circuit

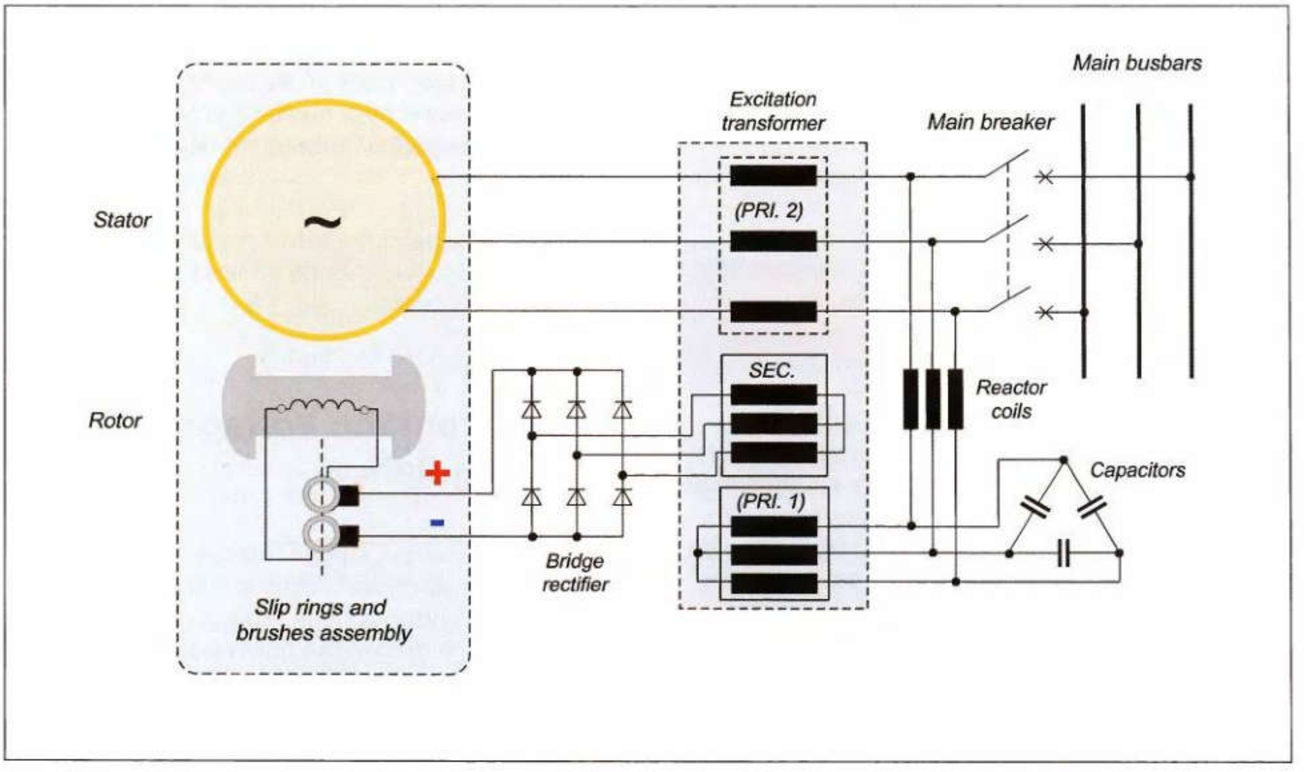


Figure 3.10 - Three-phase compound excitation circuit

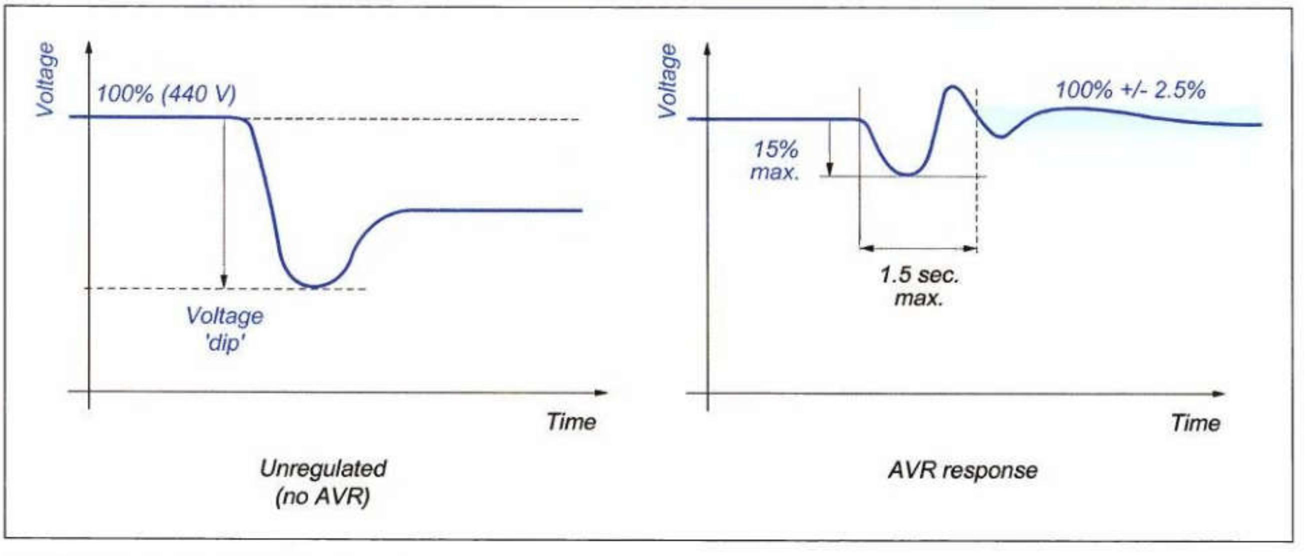


Figure 3.11 - Generator/AVR voltage response

range. This is its steady state voltage regulation. Transient voltage dip is usually limited to 15% for a specified sudden load change with recovery back to rated voltage within 1.5 seconds. In special cases where unusually large surges are expected (eg from thrusters and cargo cranes), the generator/ AVR performance limits may be extended.

The AVR senses the generator output voltage and acts to alter the field current to maintain the voltage at its set value. A manual trimmer regulator may be fitted on the generator control panel to set the voltage level eg 440 V.

More commonly, two voltage trimmer potentiometers are assembled. One is inside the generator's panel and the other is incorporated into the control card of the AVR. This option gives more flexibility to personnel for adjusting the generator's voltage.

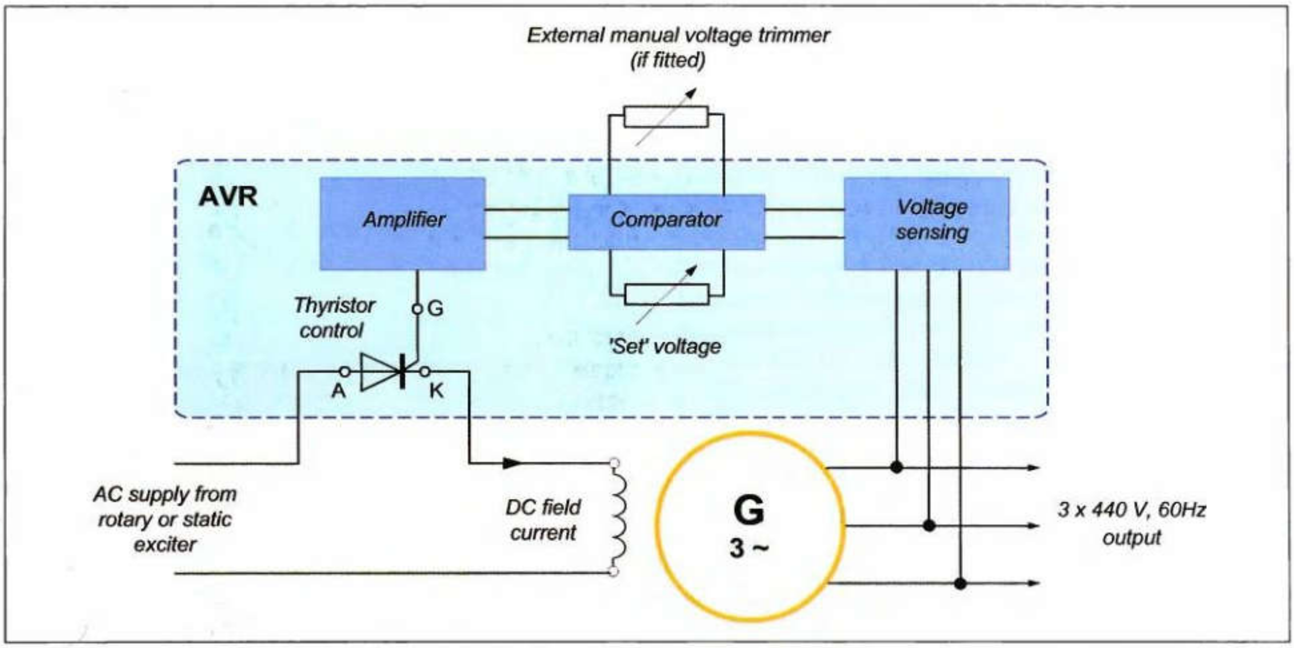


Figure 3.12 - AVR block diagram

The control circuit for a modern AVR consists of voltage and current transformers, mounted on the generator, as well as solid state elements, mounted on an electronic module fitted into the generator's termination board.

Although the AVR control circuit design varies with the manufacturer, the basic scheme contains the elements shown in Figure 3.12.

The voltage sensing unit transforms down, rectifies and smooths the generator output voltage. This produces a low voltage DC signal that is proportional to the AC generator voltage. This actual DC signal is compared with a set DC value produced by a reference circuit of zener diodes and resistors. An error signal output from the comparator is then amplified and made suitable for driving the field circuit regulating thyristor(s).

A thyristor is a fast acting electronic switch controlled by a voltage signal at its gate terminal. It rectifies and regulates the generator field current.

Additional components and sub-circuits are included in the AVR to ensure:

- Rapid response time with voltage stability
- fair current and reactive load (kVAr) sharing when generators are to be operated in parallel
- quick voltage buildup during generator run-up
- overvoltage/undervoltage alarm/trip protection.

The complete AVR circuit is fairly complex and includes a few preset variable resistors for the control of sensitivity, offset error and stability (proportional, integral and differential control). These are adjusted and set during generator trials to achieve an optimum and stable performance.

You should resist the temptation to adjust preset controls unless fully competent with such a feedback control system. However, bear in mind that, after replacing a faulty AVR, the newly assembled unit should always be adjusted.

AVR running checks, as guided by the manufacturer, consist of AC and DC voltage measurements at installed test points. These are compared with values found acceptable during previous generator trials. The voltmeter type and its range are usually specified for each test.

Most ships will carry a spare AVR unit or spare cards that may be interchanged after a suspected failure. An AVR changeover should only be attempted when its generator is stopped and locked off. Checks at the test points on the new AVR excitation field current level and the manual regulator operation (if fitted) should be proven with the generator running on no load before attempting to synchronise on to the busbars.

When generators are load sharing in parallel, check for approximately equal current (or kVAr) sharing between the machines. This will indicate correct operation of their AVRs.

QUESTION

What precaution must be taken when testing the insulation of generator cables and wiring connected to an AVR unit?

ANSWER

Electronic components, such as transistors, capacitors, integrated circuit chips (ICs), thyristors, etc, are likely to be damaged during a high voltage (500 V) megger test. To test the generator and its cables to earth and protect the electronic parts, either:

- Short-circuit all outgoing cable terminals during the IR test
- remove electronic card(s)
- disconnect all cables at both ends and test separately.

3.5 Generators in Parallel

Main generator units (gas turbine, steam turbine or diesel drives) have to be run in parallel to share a total load if it exceeds the capacity of a single machine. Changeover of main and standby generator units requires a brief parallel running period to achieve a smooth transition without blackout. For simplicity and security, it is not normally possible to run a main generator in parallel with either the emergency generator or a shore supply (except in cases where the ship's power plant is constructed to allow this type of operation). Circuit breaker interlocks are used to prevent such an arrangement.

Parallel running is achieved in the two stages of synchronising and load sharing.

Both operations are usually carried out automatically, but manual control is still in common use and is generally provided as a backup to the auto control.

The generator already on the bars is called the running machine and the generator to be brought into service is the incoming machine.

To smoothly parallel the incoming generator, it must be synchronised with the live busbars.

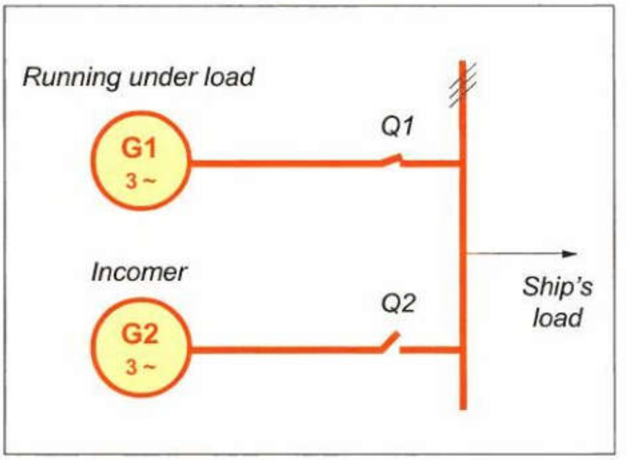


Figure 3.13 - Two generators to be synchronised

To achieve smooth manual synchronising, the incomer must be brought up to speed to obtain approximately the same frequency that is shown on the busbar frequency meter, eg 60 Hz.

QUESTION

What are the likely consequences of attempting to close the incomer's circuit breaker when the generator voltages are *not* in synchronism?

ANSWER

At the instant of closing the breaker, the voltage phase difference causes a large circulating current between the machines, which produces a large magnetic force to pull the generator voltages (and field poles) into synchronism. This means rapid acceleration of one rotor and deceleration of the other. The large forces may physically damage the generators and their prime movers, and the large circulating current may trip each generator breaker.

The incoming generator voltage is set by its AVR to be equal to the busbar voltage.

Fine tuning of the speed can now be observed on the synchroscope or synchronising lamps. The incomer is adjusted so that the synchroscope indicator rotates slowly clockwise (fast direction) at about 4 seconds per indicator revolution.

The circuit breaker should be closed as the indicator approaches the 12 o'clock (in-phase) position. The breaker closing between 5-to and 5-past the 12 o'clock synchroscope position is satisfactory as long as the pointer rotation is fairly slow.

QUESTION

What indication is available to show the optimum synchronised condition?

ANSWER

The incoming generator ammeter pointer will show very little kick when correctly synchronised.

A traditional pointer type synchroscope is usually short time rated (eg up to 20 minutes) to avoid overheating. Do not forget to switch it off after a paralleling procedure.

Modern synchroscope indicators use a circular set of LEDs that sequentially light up to show the phase difference between the generator voltages.

As a backup, or alternative, to the synchroscope, a set of lamps may be used. The correct synchronised position may be shown by either of the following methods:

- Lamps dark method (2 lamps)
- lamps bright method (2 lamps)
- sequence method (3 lamps).

In each case, the lamps are connected between the incoming generator and the busbars. The sequence method, as shown in Figure 3.15a, is preferred as it displays a rotation of lamp brightness that indicates whether the incoming machine is running fast (clockwise) or slow (anti-clockwise). As with the synchroscope, the lamp sequence must appear to rotate slowly clockwise. Correct synchronisation occurs when the top or key lamp is dark and the two bottom lamps are equally bright.

QUESTION

How could you monitor the correct instant for synchronising without the aid of a synchroscope or synchronising lamps?

ANSWER

Connect a voltmeter, as shown in Figure 3.16, (expect up to 500 V on a 440 V system) across one pole of the *open* incoming generator circuit breaker. This procedure is more easily (and *safely*) performed at the synchroscope terminals behind the door of the synchronising panel at the *front* of the main switchboard. Check the circuit diagrams before such testing.

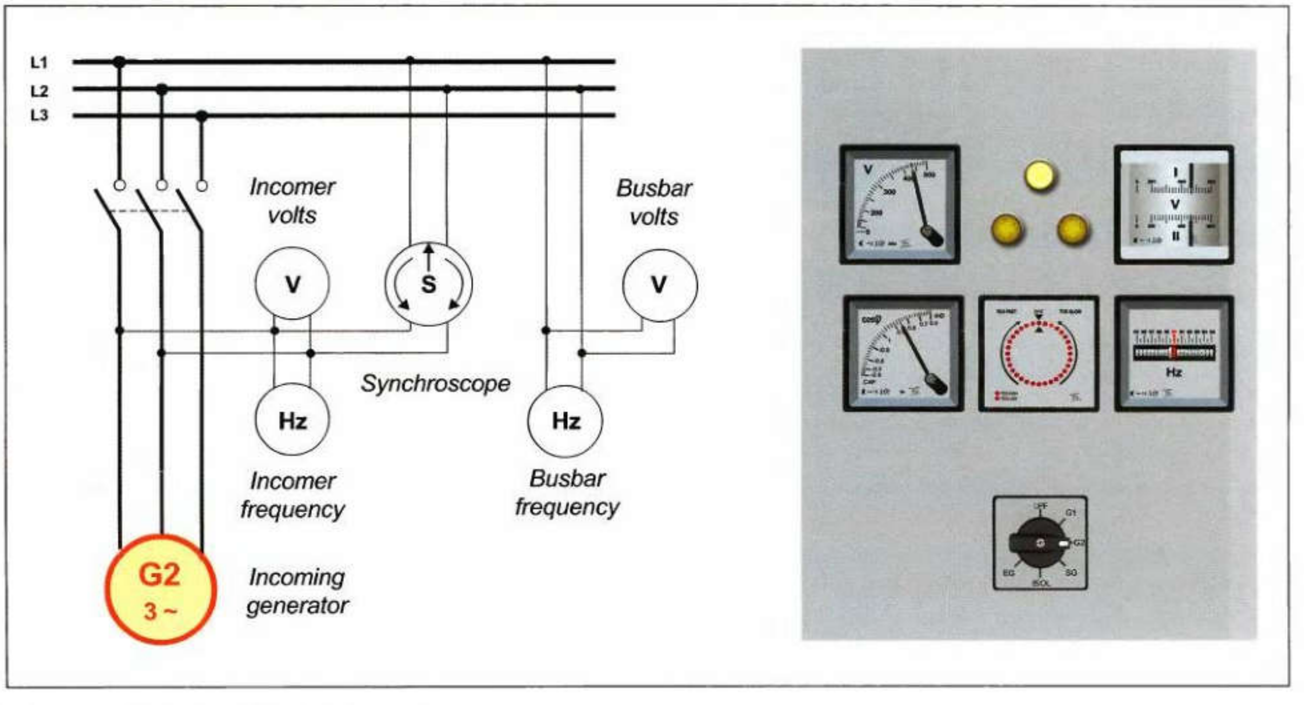


Figure 3.14 - Synchronising instruments

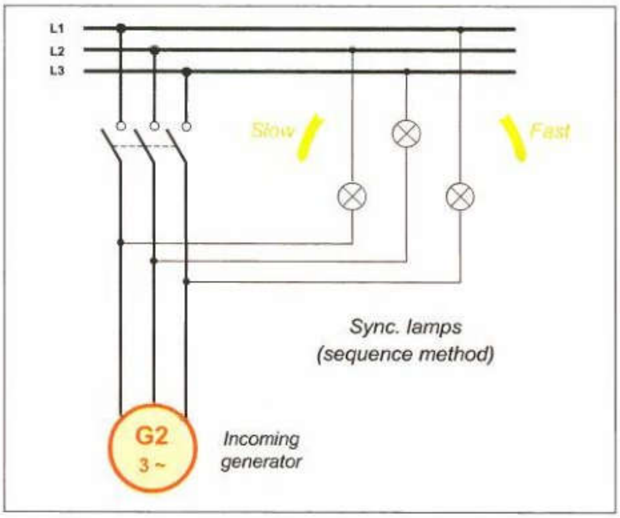


Figure 3.15a - Synchronising with three lamps

Adjust the generator speed until the voltmeter very slowly fluctuates from zero to maximum. Close the breaker when the voltmeter indication passes through zero.

A check synchronising unit, as shown in Figure 3.15b, has an electronic circuit to monitor the voltage, phase angle and frequency of the incoming generator with respect to the busbars. Circuit breaker operation is initiated by the watchkeeper, but the check synchronising monitor only allows a permit-to-close signal when all the synchronising conditions are within acceptable limits. This method provides a useful safeguard against operator error, but retains overall watchkeeper control for adjusting the voltage and frequency.

Auto synchronising of an incoming generator does everything an operator would do. It senses and controls the voltage and frequency then initiates a circuit breaker close signal at the correct instant. The auto synchronising equipment uses electronic circuits to monitor the size of voltage, frequency and phase angle difference, then acts to regulate them until they are equal to the existing busbar conditions.

Usually, the check or auto synchroniser units are switched between a set of generators as and when required.

Figure 3.15b - Synchronising unit

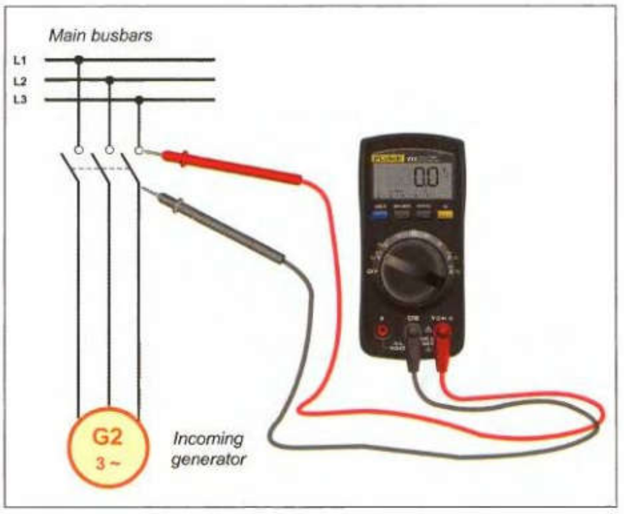


Figure 3.16 - Synchronising with a voltmeter

When an incoming generator has been successfully synchronised, the synchronising equipment should be switched off.

The total busbar load can now be shared between generators or totally transferred to the new machine. In parallel operation, a generator governor directly controls power (kW), while its AVR trimmer controls reactive power (kVAr) or 'power factor'.

Manual kW load sharing is achieved by raising the governor setting of the incoming machine while lowering the setting on the running machine. The balance of power sharing is dictated by the governor (speed) droop of each generator prime mover. Current (or kVAr) sharing is set by the voltage droop of each generator AVR.

For equal load sharing of kW and kVAr, each machine must have similar droop characteristics, which are typically 2-4% between no-load and full-load values.

An overall balance of load sharing for kW and kVAr can be seen by comparing the power factor (*cos*φ) meters of each generator.

Autoload sharing equipment compares the kW loading of each generator (via CTs and VTs) and any difference is used to provide an error signal to raise/lower the governor setting of each prime mover as necessary. The equipment is usually trouble free, requiring little maintenance other than an occasional visual inspection, cleaning and checking the tightness of the connections.

Manual load sharing is the normal fallback if the auto control equipment fails.

QUESTION

Two generators are load sharing in parallel:

Generator 1 delivers 500 kW at 0.8 power factor lag, and

Generator 2 delivers 400 kW and 350 kVAr lag.

Calculate:

(a) the kVAr loading of Generator 1

(b) the pf of Generator 2

(c) the total busbar loading in kW, kVAr and power factor.

ANSWER

(a) $\cos\varphi_1 = 0.8$

so
$\varphi_1 = 36.9°$

now (from PQS power triangle):
$Q = P \times \tan\varphi_1 = 500 \times \tan 36.9° = $ ***375 kVAr***

(b) $\tan\varphi_2 = \dfrac{Q_2}{P_2} = \dfrac{350}{400} = 0.875$

so
$\varphi_2 = 41.2°$
then,
$pf_2 = \cos\varphi_2 = \cos 41.2°$
$= $ ***0.75 Lagging***

Total $P = 500 + 400 = $ ***900 kW***

and Total $Q = 375 + 350 = $ ***725 kVAr***

(c) *Overall* $\tan\varphi = \dfrac{Q}{P} = \dfrac{725}{900} = 0.81$
and $\varphi = 38.9°$

so,
overall load pf $= \cos 38.9°$
$= $ ***0.78 Lagging***

QUESTION

Two generators are load sharing equally in parallel when a total loss of excitation occurs in No. 2 machine. What is the likely outcome?

ANSWER

Generator No. 2 will run as an induction generator, drawing its excitation kVAr from No. 1. Both generator currents will rise rapidly with No. 1 becoming more lagging while No. 2 runs with a leading pf (indicated on cosφ meter). A loss of excitation trip (if fitted) or the overcurrent relay should trip No. 2 generator probably causing an overload on No. 1. Alternatively, No. 1 trips on overcurrent, which deprives No. 2 of excitation and its breaker trips out on undervoltage.

Result – total power failure!

3.6 Emergency Generators

The power rating of an emergency generator is determined by the size and role of the ship. On smaller vessels, a few kW will suffice for emergency lighting only. Larger and more complicated vessels, such as LPG carriers or passenger liners, may require hundreds of kW for emergency lighting, re-starting of the main engine auxiliaries and to supply firefighting pumps.

The construction and operation of an emergency generator is similar to that of a main generator. Excitation supplies, either static or rotary, will usually be governed by an automatic voltage regulator.

Generally, the emergency generator output voltage is at the same level as that of the main generators, eg 440 V, 60 Hz, three-phase AC. In an HV/LV system, eg 6.6 kV/440 V, the emergency generator will usually operate at 440 V and the emergency switchboard will be interconnected with the engine room 440 V main switchboard in normal operation.

It is not normally possible to synchronise the emergency and main generators. Special interlocks in the control circuits of the circuit breakers, at each end of the interconnector, prevent parallel running.

In normal operation, the emergency board is supplied from the main switchboard by a feeder called the transfer line.

However, when cargo vessels are moored at a berth, for example, the emergency generator can be used as a harbour generator and run in parallel with main generators if needed. Therefore, in this situation, synchronisation should be provided as it also offers a reduced maintenance requirement for main DG units.

In the event of main power failure, the emergency generator prime mover should start automatically. The run-up is initiated by an electrical relay that monitors the normal voltage supply (eg 440 V) at the side of the emergency switchboard which, in normal operation, is connected to the main switchboard via the transfer line.

Falling mains voltage causes the startup relay to operate the emergency generator prime mover's starter.

The prime mover may be electrically cranked from its own 24 V battery and starter motor or, for example, be started from its own hydraulically-driven hand starter and accumulator reservoir fitted locally to the emergency generator engine.

A manual startup may be initiated by push buttons in the emergency generator room.

Correct functioning of the auto-start equipment is vital to the production of emergency power.

Weekly testing of the emergency generator should include simulation of the loss of normal power. This can be achieved by switching off a transfer line circuit breaker at the side of the main switchboard. In turn, the emergency switchboard will be blacked out and, as a result, automatic starting of the emergency generator should be initiated along with its circuit breaker switching to supply the emergency consumers.

Emergency generators should be regularly checked and run up to speed for short test runs to comply with safety regulations. These no-load running checks should, when practicable, be supplemented occasionally by an actual load test. This requires the disconnection of normal mains power from the emergency board while the emergency generator is loaded up to near its rated value. Only a proper load test will prove the performance of the emergency generator, its prime mover and the circuit breaker operation.

3.7 Generator Protection

Other than through direct temperature measurement of the stator windings and the internal air, the protection of a generator is largely based on the sensing of current and voltage from CTs and VTs. The number and type of protective relay functions increases with the generator kVA rating and voltage level. Electronic protective relays are mounted inside the generator's main switchboard panel. Protection can be also provided by the generator's circuit breaker PLC-based logic module. Some protective functions may be grouped together within a single relay case. Settings for level and time delay must be periodically checked by injecting currents and/or voltages directly into the relay (usually via a special multi-pole socket adjacent to the relay and internally wired to it). See Chapter 2 for general circuit protection methods.

Some typical relay types employed for generator protection are outlined in Figure 3.17.

Overcurrent Inverse Time (OCIT)

The OCIT relay function monitors general balanced overloading and has current/time settings determined by the overall protective discrimination scheme.

Typical setting ranges for current (I) and time (t) are:

$I> = 0.7-2 \times In$

(In = normal or rated generator current)

and

$t = 1-10s.$

OC (INST)

'Instantaneous' trip to protect against extremely high overcurrent caused by a short-circuit fault. Typical setting ranges are:

$I>> = 2-10 \times In$

and

$t = 0.1-1s.$

Negative Phase Sequence (NPS)

An NPS relay determines the amount of unbalance in the stator currents, which is an indirect measure of the generator stator and rotor temperature. A relatively small degree of unbalance causes a significantly increased temperature rise, so the NPS current setting is low at around $0.2 \times In$.

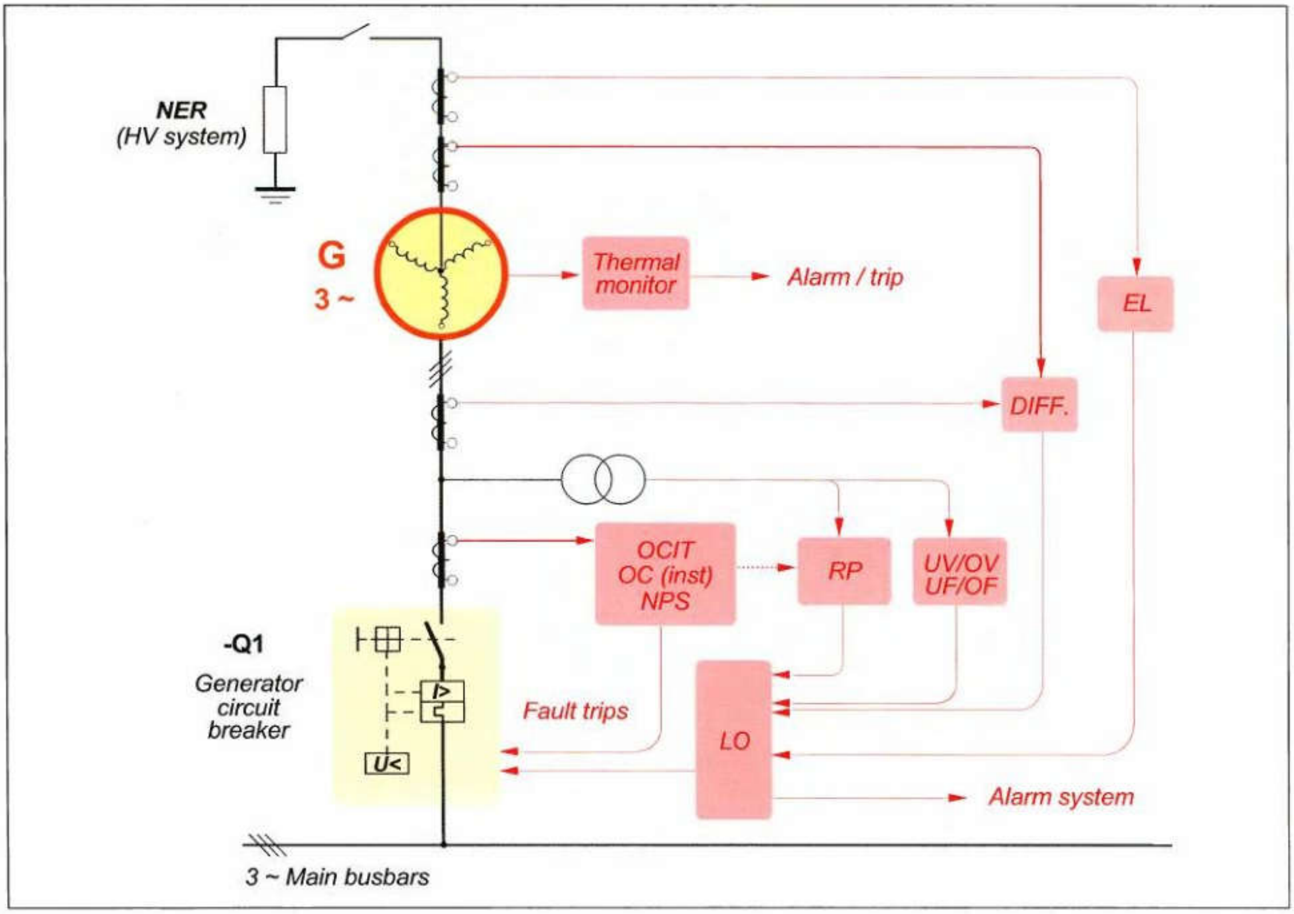


Figure 3.17 - Generator protection scheme

Differential (DIFF)

This is a DIFF measurement of current at each end of a stator phase winding. This comparison of current is to detect an internal fault in the stator windings, which may be caused by partially short-circuited coil turns and/or earth faults.

Current settings for this very serious fault are very low, eg about 0.1 × In.

Earth Leakage (EL)

An EL relay (sometimes called zero phase sequence) detects an earth fault current returning back through the earthed neutral connection. In a ship's HV generator system, the earth fault current is limited by a high impedance neutral earthing resistor (NER), or earthing transformer, so the pick-up current setting is very low, eg 1-5A with a time delay of 0.1-0.5s.

Undervoltage and Overvoltage (UV/OV)

UV/OV functions are monitored with settings of around 0.8.Un and 1.2.Un (Un = rated voltage), with time delays of about 2s. A UV function may not be required in many protection schemes.

Under and Over Frequency (UF/OF)

UF/OF settings are typically 58 Hz and 62 Hz for a 60 Hz system (48 Hz and 52 Hz for a 50 Hz system).

Lock Out (LO)

This is the master LO or trip/hand-reset relay responsible for tripping the generator circuit breaker. Its action is instantaneous when triggered by a protective relay. It can also be used to trip the generator prime mover, and initiate generator field suppression together with the signalling of an alarm.

Reverse Power Protection (RP)

Generators intended to operate in parallel must have RP.

An RP relay monitors the direction of power flowing between the generator and the load. If a prime mover failure occurs, the generator acts as a motor. The RP relay detects this fault and acts to trip the generator circuit breaker.

The pick-up power level setting and time delay setting are adjustable and are preset to suit the prime mover. If the prime mover is a turbine, very little power is absorbed when motoring and a reverse power pick-up setting of 2-3% is usual. If the prime mover is a diesel, a setting range of 5-15% is usually adopted. A time delay range of about 0.5-3s is usual.

The RP relay operation is easily checked during a generator changeover. The outgoing generator is gradually throttled down so that it motors, causing the reverse power relay to trip its generator circuit breaker.

3.8 Generator Maintenance

Regular inspection and the correct maintenance of generators and their associated control gear is essential to prevent failure and inefficient operation.

Always ensure that the generator prime mover is shut down and locked off before you begin any maintenance. Also ensure that the generator circuit breaker is locked off, auto-start circuits are disabled and that electric heaters are switched off and isolated.

All wiring to the generator should be inspected for damage or frayed insulation and tightness of terminal connections.

Check for signs of oil and water contamination of cable insulation within terminal boxes.

Check that the cooling air intake and exhaust openings are not blocked and are free of dirt and dust.

Inspect and clean the generator rotor and stator windings by removing dust with a dry, lint-free cloth. Low pressure, dry compressed air may be used to dislodge heavier dirt, but be careful not to drive the dirt deeper into the windings. An industrial vacuum cleaner is very effective for removing dirt from the windings. Use a rubber or plastic coated nozzle on the vacuum cleaner tube to prevent abrasive damage to the sensitive winding insulation. Oil on the surface of winding insulation will reduce the insulation resistance and shorten its life. The oily deposits can be removed by washing the windings with special slow or fast drying degreasant liquids. Minor abrasions to winding insulation can be repaired, after cleaning, by the application of a suitable air drying insulating varnish.

Brushless generators usually require less maintenance. Generators with static excitation systems require additional care. Rotor slip rings must be checked for uniform (even) wear and that the carbon brushes have free movement in their boxes. Correct brush pressure can be checked using a pull-type spring balance and then comparing it with the manufacturer's instructions. A pull of around 1-1.5 kg is usual. If the brushes become too short (below about 2 cm), the reduced spring pressure will cause sparking at the slip ring contact. Replace brushes with the correct type and bed them to the curvature of the slip rings. This can be done by placing a thin strip of glass paper (not emery paper) over the slip ring, with its cutting surface under the carbon brush. Pull the glass paper around the slip ring until the brush surface has the same contour as the ring. The last few passes of the glass paper should be made in the same direction as the normal rotor direction. Remove all traces of carbon dust with a vacuum cleaner.

Generator excitation transformers, AVR components and rotating diodes must be kept free of dirt, oil and dampness. A special contact grease is used between the diode connections to prevent electrolytic action occurring between dissimilar metals.

Check contacts for tightness but do not disturb them unnecessarily.

Measure the insulation of the stator and rotor windings to earth and between stator phases (assuming that the neutral point is available for disconnection at the terminal box).

Remember to disconnect or short-circuit any electronic circuit components that are likely to be damaged by a high voltage insulation test. Consult the wiring diagrams and the manufacturer's instructions before testing. Record the IR values and note the prevailing temperature and humidity.

Compare with previous test results. A minimum IR value is usually taken to be 1 MΩ, but a lower value may be acceptable to a surveyor based on 1 kΩ/volt, eg 450 kΩ or 0.45 MΩ for a 450 V generator. However, it is the historical trend of the machine IR values that will provide a better picture of the insulation condition.

Generators with very low IR values (less than 0.5 MΩ) should be given a thorough cleaning then dried out. If the IR has recovered to a reasonable value, which has become steady during the drying period, its windings should be covered with high quality air drying insulating varnish. Should the IR value remain low during a dry-out, the machine insulation needs to be completely reimpregnated or rewound (generally by a shore-based workshop).

After maintenance, no-load running checks should precede synchronising and loading. On load, it is important to check for excess temperature rise and load-sharing stability when running in parallel.

Finally, if a generator is to be left idle for a long time, make sure that its windings are suitably heated to prevent internal condensation forming on its insulation.

With all electrical equipment – dirt, overheating and dampness are the enemy!

3.9 Main Switchboard

A typical ship's main switchboard is shown in Figure 3.18.

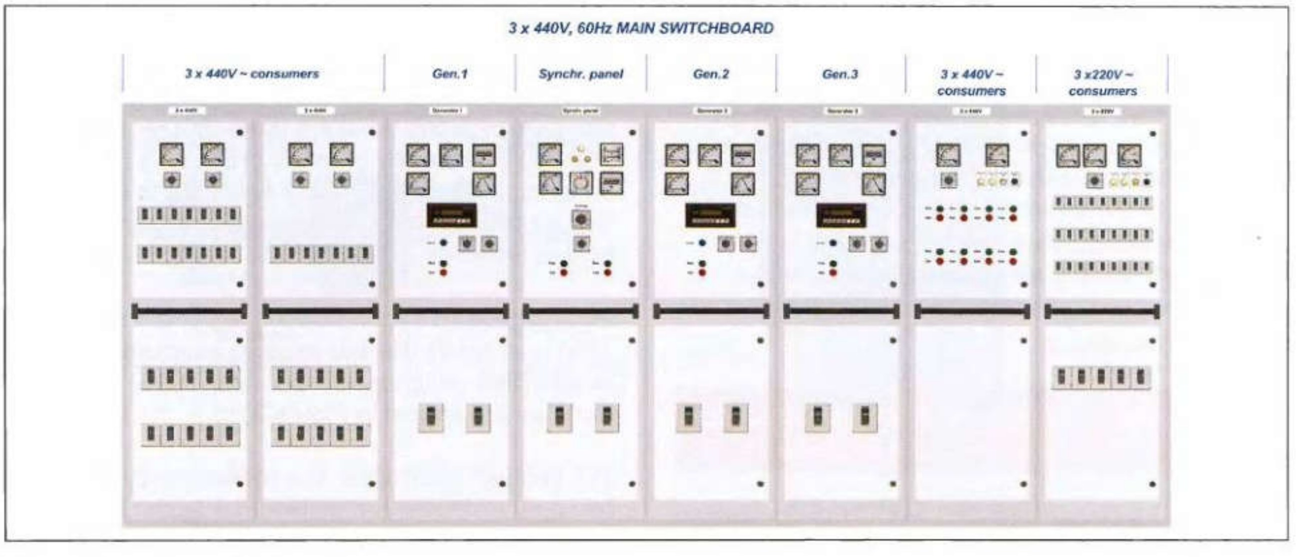


Figure 3.18 - Main switchboard

The central section of the main switchboard is used for the control of the main generators. The switchgear cubicles on either side of the generator panels are used for essential services and, flanking these, are the grouped motor starter panels.

In some cases (including HV systems), handles for opening the panel's doors on switchboard cubicles are usually linked (or interlocked) to an isolating switch. This ensures that supplies to components in the cubicle are switched off before the door can be opened.

Fused isolators are isolating switches that incorporate fuses. The action of opening the switch isolates the fuses so that they can be replaced safely.

Fused isolators can also be interlocked with the cubicle door handle. Motor starters frequently incorporate this arrangement.

One type of interlocked fused isolator can be completely withdrawn and removed to ensure complete safety when carrying out maintenance on equipment.

Maintenance on fused isolators consists of periodically checking the operating mechanism. Contacts must be inspected for damage and lightly greased with an electrical lubricant. The interlock mechanism (if fitted) should also be examined for correct and safe operation.

A separate section switches the three-phase 220 V AC low power and lighting services.

The 440/220 V lighting transformers are generally mounted near the main switchboard (often in the engine control room).

The main generator supply cables are connected directly to their respective circuit breakers. Short copper bars from each generator circuit breaker connect it to the three busbars that run through the length of the switchboard. The busbars may be seen if the rear doors of the switchboard cubicle are opened, but it is also possible they are in a special enclosed busbar duct acting as an internal fire barrier.

Take care when opening doors on switchboards. Live parts are exposed – you are in danger.

The ship's electrical diagrams will include drawings of the front, and perhaps the rear, of the main switchboard, showing the fitted equipment.

The electrical distribution diagrams will follow the physical arrangement of the main switchboard layout. You should study the electrical circuit and layout diagrams for your ship to identify, locate and appreciate the role of each key component in the scheme. Efficient fault finding on a distribution network can only be achieved with a thorough understanding of the scheme and its normal operation.

Switchboard instruments and controls for particular functions are grouped together. For example, the generator synchronising panel has all the instruments, relays and switches necessary for generator paralleling.

Each generator panel has all the instruments, relays, switches, controls and status lamps necessary for control of the generators. The instruments on panels of outgoing circuits are usually limited to an ammeter, status lamps, function switches (eg manual/off/auto) and push buttons.

Low power control and instrument wiring is of relatively small cross-section, with multi-coloured plastic insulation that is clearly identified against the larger main power cables.

The instrumentation and control wiring is supplied from fuses that are located behind the appropriate panel. Green and yellow striped earth wiring from instruments and panel doors, etc, is connected to a common copper earth bonding bar running the length of the switchboard at its rear. This earth bar is electrically bonded to the ship's steel hull.

3.10 Main Circuit Breakers

LV generator circuit breakers and other large distribution circuit breakers (600-6000 A) on board ship are traditionally of an air break type called an air circuit breaker (ACB). This means that the circuit breaker contacts separate in air. An ACB outline is shown in Figure 3.19.

High voltage (HV) installations, eg at 6.6 kV and 11 kV, generally use the vacuum interrupter type or gas-filled (sulphur hexafluoride – SF6) breakers. Outlines are shown in Figure 3.20.

In a vacuum interrupter, the contacts only need to be separated by a few millimetres as the insulation level of a vacuum is extremely high. The quality of the vacuum in the sealed interrupter chamber is checked by applying a short duration HV pulse (eg 10 kV for a 6.6 kV breaker) across the open contacts.

In the gas breaker, the contacts separate in a special interrupter chamber containing SF6 gas, typically at 500 kPa (5 bar) at 20°C.

The operating mechanism for vacuum and SF6 breakers is similar to that employed for an ACB.

Figure 3.21 shows how each main circuit breaker is mounted on guide rails inside a main switchboard cubicle, from which it must be withdrawn and isolated from the busbars for maintenance and testing.

The breaker and its guide rails are usually mounted in a special cassette bolted into the switchboard cubicle and electrically connected to the busbars.

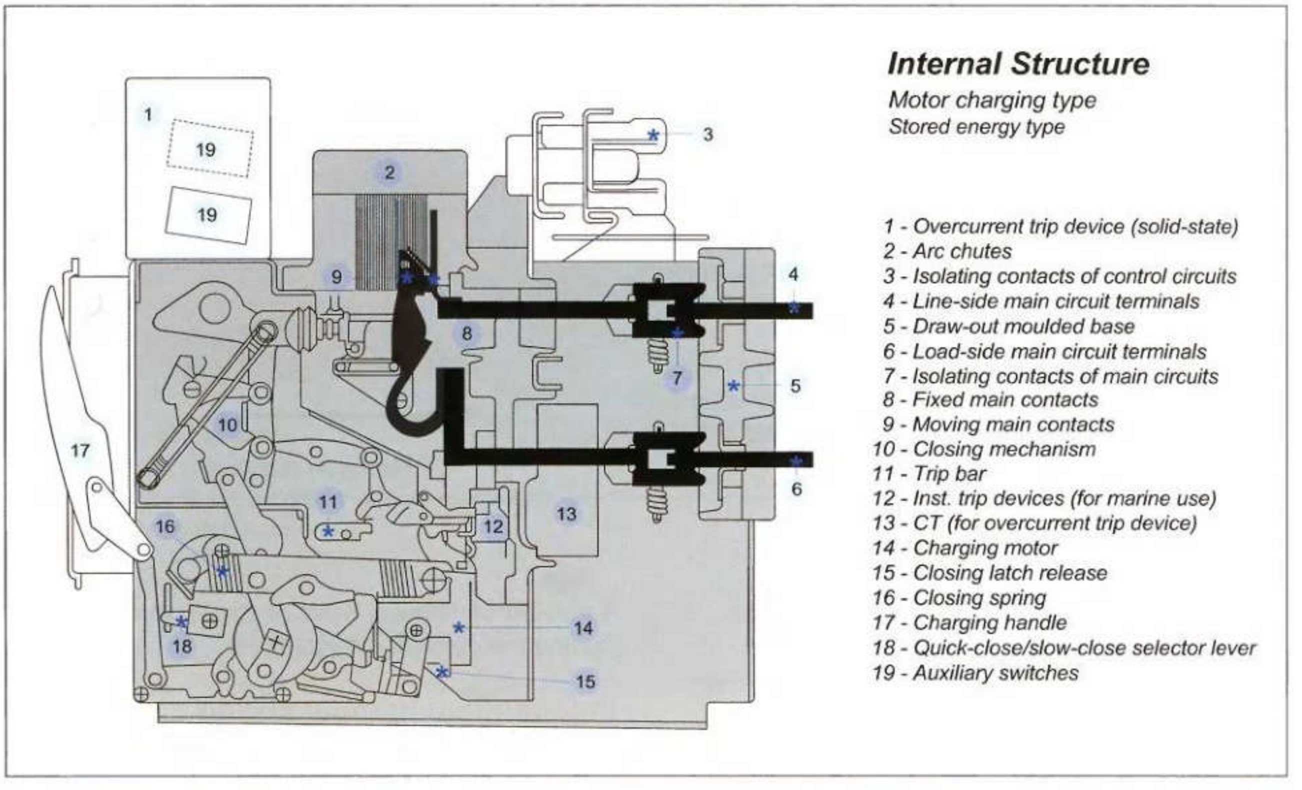


Figure 3.19 - Air circuit breaker components

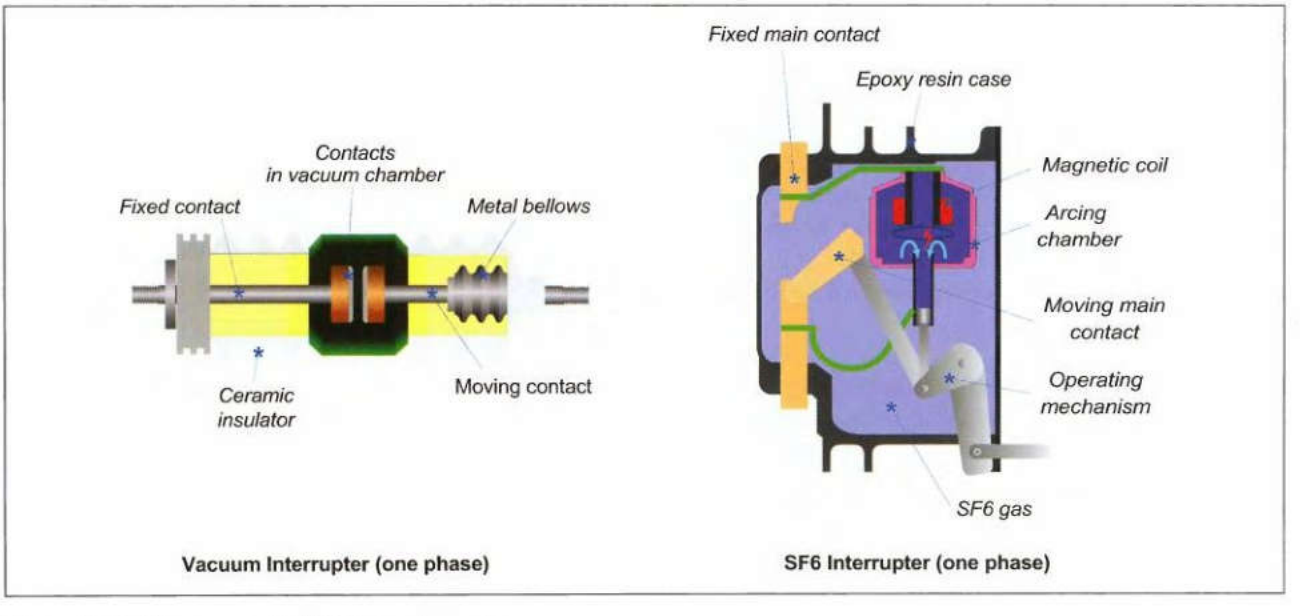


Figure 3.20 - Vacuum and SF6 interrupter units

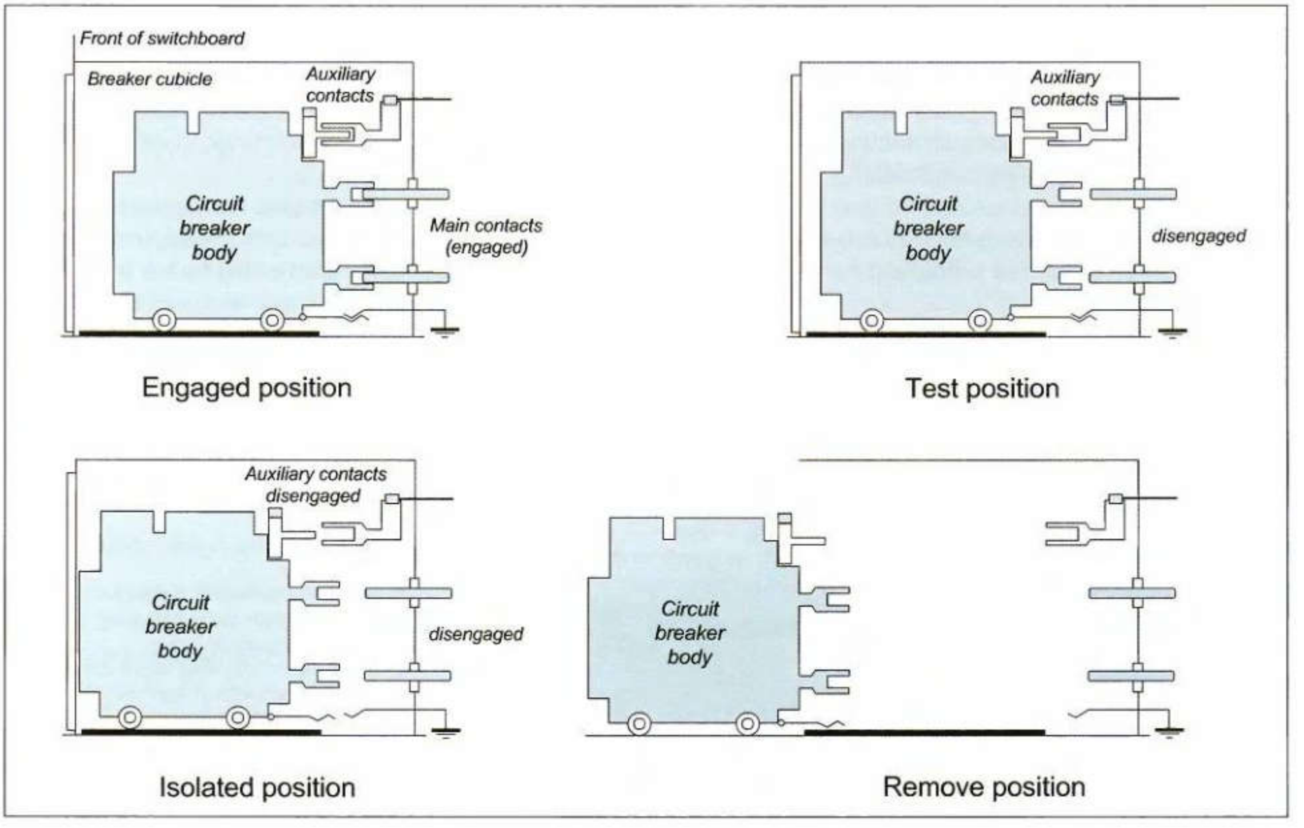


Figure 3.21 - Circuit breaker positions

If repair work demands that the breaker is to be completely removed from its cassette, then a special hoist or fork lift is usually required for large, heavy duty units.

The action of withdrawing the circuit breaker causes a safety shutter to cover the live busbar contacts at the rear of its cubicle. The mechanical linkage in a circuit breaker is quite complex and should not be interfered with except for maintenance and lubrication as specified by the manufacturer.

The main fixed and moving contacts are of copper (sometimes of special arc-resistant alloy or silver tipped) and usually silver alloy coated. Main contacts should not be scraped or filed. If the main contacts suffer severe burning they will probably require realignment.

Arcing contacts normally suffer burning and may be dressed by a smooth file. Carborundum and emery should not be used – the hard particles can embed themselves in the soft contacts and cause future trouble.

Arc chutes, or arc splitter boxes, confine and control the arc to rapidly accelerate its extinction. These must be removed and inspected for broken parts and erosion of the splitter plates.

A number of different types of circuit breaker closing mechanism may be fitted.

Independent manual spring

The spring charge is directly applied by manual depression of the closing handle. The last few centimetres of handle movement releases the spring to close the breaker. Closing speed is independent of the operator.

Motor-driven stored charge spring

This is the most common type for marine applications. Closing springs are charged by a motor gearbox unit. Spring recharging is automatic following closure of the breaker, which is initiated by a push button. This may be a direct mechanical release of the charged spring or, more commonly, an electrical release via a solenoid latch.

Manual-wound stored charge spring

This is similar to a motor-driven stored charge spring, but with manually charged closing springs.

Solenoid

The breaker is closed by a DC solenoid energised from the generator or busbars via a transformer/ rectifier unit, contactor, push button and, sometimes, a timing relay.

Circuit breakers are held in the closed or ON position by a mechanical latch. The breaker is tripped by releasing this latch, allowing the kick-off springs and contact pressure to force the contacts open.

> ***WARNING:*** Circuit breakers store energy in their springs for:
>
> - Store charge mechanisms in the closing springs
> - contact and kick-off springs.
>
> Extreme care must be exercised when handling circuit breakers when either the closing springs are charged or the circuit breaker is in the *ON* position.
>
> Isolated circuit breakers racked out for maintenance should be left with the closing springs *discharged* and in the *OFF* position.

Tripping can be initiated:

- Manually – a push button with mechanical linkage trips the latch
- undervoltage release (trips when de-energised)
- overcurrent/short-circuit trip device or relay (trips when energised)
- solenoid trip coil – when energised by a remote push button or relay (such as an electronic overcurrent relay).

Mechanical interlocks are fitted to main circuit breakers to prevent racking out if still in the ON position.

Care must be taken not to exert undue force if the breaker will not move as damage may be caused to the interlocks and other mechanical parts.

Electrical interlock switches are connected into circuit breaker control circuits to prevent incorrect sequence operation, eg when a shore supply breaker is closed onto a switchboard.

The ship's generator breakers are usually interlocked OFF to prevent parallel running of a ship's generator and the shore supply.

Chapter Four
Motors and Starters

The drive power for almost all gears on board ship (eg thrusters, cargo gears, mooring winches, pumps, compressors and fans) comes from electric motors, the most common of which is the three-phase AC cage rotor induction motor. It is popular because it is simple, tough and requires very little attention, and it starts and stops with simple and reliable motor starters.

Three-phase induction motors are usually supplied at 440 V, 60 Hz (380 V, 50 Hz), but 3.3 kV and 6.6 kV, 60 Hz are sometimes used for bow thrusters and cargo gears.

Special types of motor found on ships include DC commutator motors for driving deck machinery where speed control is important, and single-phase AC motors in galley equipment and domestic tools.

High power synchronous AC motors are frequently used for electric propulsion drives (see Chapter 8).

This chapter will deal principally with the three-phase AC cage rotor induction motor, together with its control and protection. The more common types of motor speed control methods are also discussed, followed by maintenance procedures for motors and starters.

4.1 Motor Construction

The induction motor has two main components, the stator and the rotor. The stator carries three separate insulated phase windings that are spaced 120° (electrical) apart and lying in slots cut into a laminated steel magnetic core. This type of stator winding is similar to the construction used for an AC generator. 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 AC power supply.

The rotor winding consists of copper or aluminium conductor bars that are connected together at their ends by short-circuiting rings to form a cage winding. The conductor bars are set in a laminated steel magnetic core. The essential reliability of the induction motor comes from having this type of simple, robust rotor, which usually has no insulation on the conductor bars and does not have any troublesome rotary contacts such as brushes, commutator or slip rings. Figure 4.1 shows the main items used in the construction of a typical totally enclosed, fan ventilated (TEFV) induction motor.

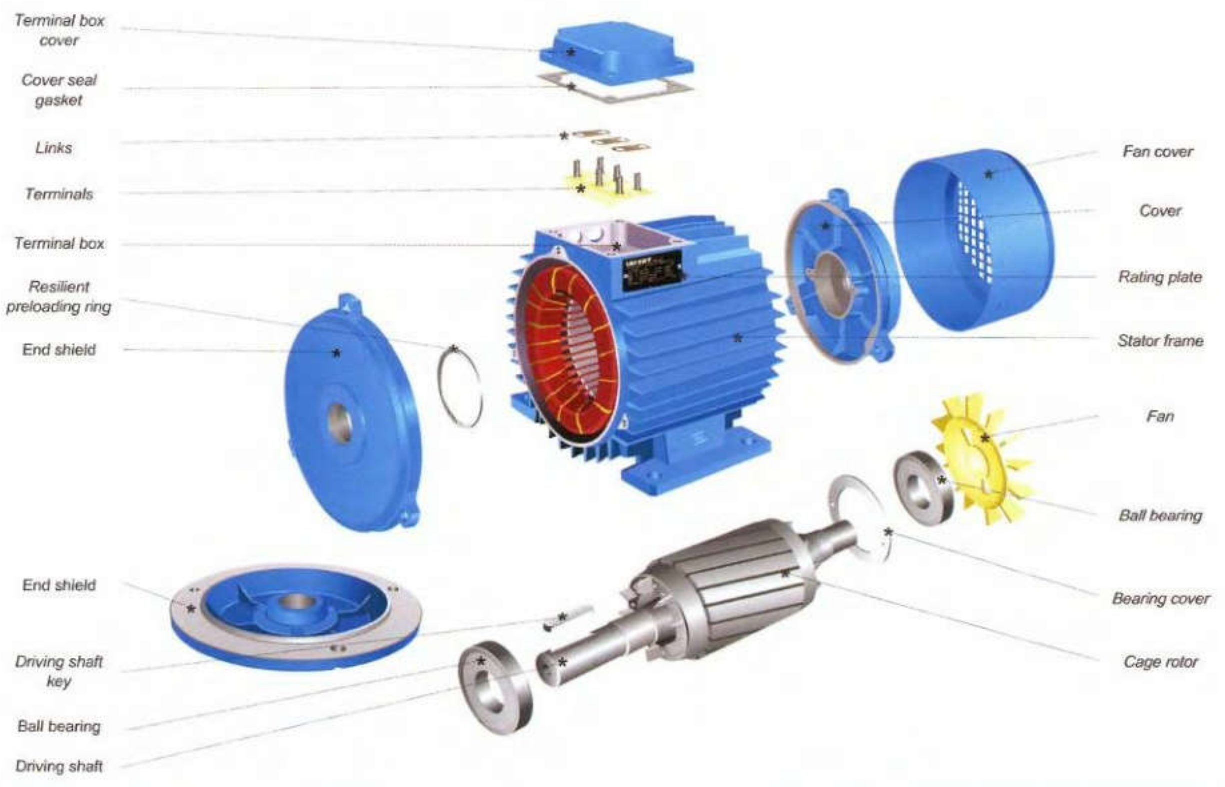
4.2 Enclosures and Ratings

Motor Enclosures

Enclosure protection for electrical equipment is defined in terms of its opposition to the ingress of solid particles and liquids. The enclosure protection is defined by the ingress protection (IP) Code, where a two figure number is used to indicate the degree of protection against the ingress of solids and liquids.

Drip-proof, open ventilated motors are used where the risk of liquids leaking from overhead pipes and valves may be a problem. Air is drawn into the machine by an internal fan to provide cooling. The ventilation ducts are fitted with mesh screens to prevent any objects from entering the motor and causing damage. The screens must always be kept clean and free from dust or the motor will overheat due to inadequate ventilation.

When a greater degree of protection is required, the enclosure is made TEFV and jet-proof. No external air is allowed inside the motor. To improve heat transfer, the motor casing is finned to increase the surface area, and airflow across the fins is achieved by means of an external fan and cowl arrangement.



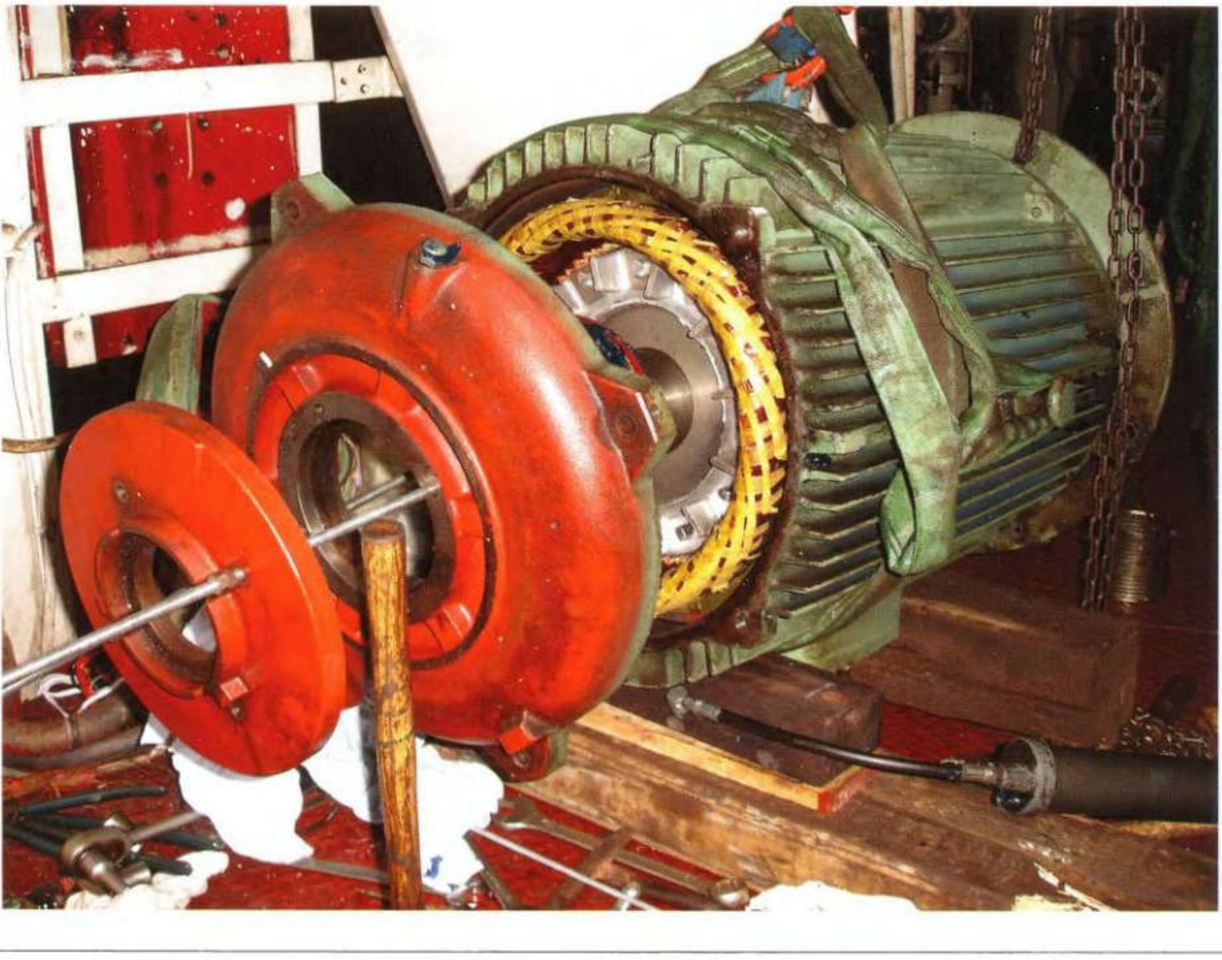


Figure 4.1 - Induction motor components

Motors located outside on weather decks have deck watertight enclosures, but the external fan is omitted because of the possibility of ice formation.

Deck watertight motors (IP56) have sealed bearings and a watertight terminal box. They can be completely immersed in shallow water for short periods. Sealing washers are fitted under all screws and a coat of special corrosion-resisting paint is generally applied to all external and internal surfaces.

Figure 4.2 - TEFV motor enclosure

1st numeral	**Degree of Protection** against contact with live or moving parts inside the enclosure and protection of equipment against ingress of *solid bodies.*	2nd numeral	**Degree of Protection** against ingress of *liquids*
0	No protection of persons against contact with live or moving parts inside the enclosure. No protection of equipment against ingress of solid foreign bodies.	0	No protection
1	Protection against accidental or inadvertent contact with live or moving parts inside the enclosure by a large surface of the human body, for example, a hand but not protection against deliberate access to such parts. Protection against ingress of large solid foreign bodies.	1	Protection against drops of condensed water: Drops of condensed water falling on the enclosure shall have no harmful effect.
2	Protection against contact with live or moving parts inside the enclosure by fingers. Protection against ingress of medium size solid foreign bodies.	2	Protection against drops of liquid: Drops of falling liquid shall have no harmful effect when the enclosure is tilted at any angle up to 15° from the vertical.
3	Protection against contact with live or moving parts inside the enclosure by tools, wires or such objects of thickness greater than 2.5 mm. Protection against ingress of small solid foreign bodies.	3	Protection against rain: Water falling in rain at an angle up to 60° with respect to the vertical shall have no harmful effect.
4	Protection against contact with live or moving parts inside the enclosure by tools, wires or such objects of thickness greater than 1 mm. Protection against ingress of small solid foreign bodies.	4	Protection against splashing: Liquid splashed from any direction shall have no harmful effect.
5	Complete protection against contact with live or moving parts inside the enclosure. Protection against harmful deposits of dust. The ingress of dust is not totally prevented, but dust cannot enter in an amount sufficient to interfere with satisfactory operation of the equipment enclosed.	5	Protection against water-jets: Water projected by a nozzle from any direction under stated conditions shall have no harmful effect.
6	Complete protection against contact with live or moving parts inside the enclosure. Protection against ingress of dust.	6	Protection against conditions on ships' decks (deck watertight equipment): Water from heavy seas shall not enter the enclosure under prescribed conditions.
Note that the higher the numeral of the 1st and 2nd characteristic, the greater degree of protection the enclosure offers:		7	Protection against immersion in water: It must not be possible for water to enter the enclosure under stated conditions of pressure and time.
eg Jet-proof IP55 meets all the less onerous degrees such as IP22, IP23, IP34 and IP54.		8	Protection against indefinite immersion in water under specified pressure. It must not be possible for water to enter the enclosure.

Motor Ratings

The motor converts electrical energy taken from the electric power supply into rotational mechanical energy at the motor shaft. Power losses occur during the energy conversion, which results in the production of heat in the motor. The losses increase when the load on the motor increases because the motor takes more current from the supply.

The life of the insulating materials used on motor windings depends on the temperature at which it is operated. Insulating materials are selected for marine practice based on an ambient temperature of 45°C. An adequate lifespan for the insulation is based on the assumption that the maximum temperature limit is not exceeded.

Motor nameplate definitions:

Rated full load current (FLC)

This is the maximum value of current that the motor can continuously take from the supply without exceeding the temperature limit for the insulating materials used.

Rated voltage

The motor has been designed to operate successfully when connected to this value of supply voltage. If the supply voltage exceeds the rated voltage limit, overheating, stalling and burnout of the stator winding can result.

Rated frequency

Motor speed and motor losses are directly affected by the supply frequency. If the motor is operated at any frequency other than the one it is rated at, overheating can occur.

Power rating

This is the shaft power output of the motor when it is connected to rated voltage and frequency when drawing its rated current from the supply.

Rated speed

This is the full load speed of the motor when connected to rated voltage and frequency.

IP number

Indicates the degree of protection given by the motor enclosure.

The motor rating details are shown on the motor nameplate as in the example in Figure 4.3.

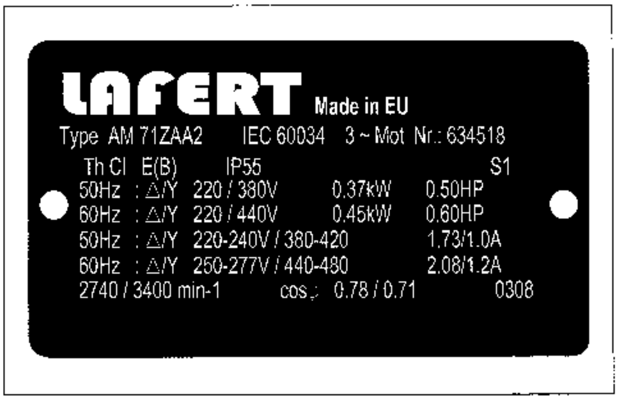


Figure 4.3 - Motor rating label

Standard three-phase AC induction motors are manufactured in about 60 frame sizes, with power ratings from about 0.37 kW to 500 kW. Table 4.1 shows a sample selection of output power ratings and their average full load current (FLC) for 4-pole, 440 V motors.

kW	0.55	1.5	4.0	11	22	37	55	75	100	200	500
A	1.4	3.1	7.9	20.1	39	64	90	125	162	321	780

Table 4.1 - Output power ratings

4.3 Induction Motor Operation

When the three-phase AC supply voltages are connected to the three stator phase windings, the resulting phase currents produce a multi-pole magnetic flux (Φ). This flux is physically rotated around the stator core by the switched sequence of the L1-L2-L3 currents at a speed called synchronous speed (n_s). The value of synchronous speed depends on how many magnetic pole-pairs (p) are fixed by the stator winding arrangement and by the frequency (f) of the voltage supply connected to the stator winding.

$$n_s = \frac{f}{p} \text{ rev/s} \quad \text{or} \quad N_s = \frac{f \times 60}{p} \text{ rev/min}$$

QUESTION

What is the synchronous speed of a 6-pole motor supplied at 60 Hz?

ANSWER

20 rev/s or 1200 rev/min

The stator rotating magnetic flux cuts through the rotor conductors to induce an alternating emf into them. Since the rotor conductors are connected together at the ends, the induced emfs set up rotor currents.

The rotor currents also produce a magnetic flux that interacts with the stator rotating flux, which produces a torque (T) on the rotor conductor bars, as shown in Figure 4.4.

Rotor torque size is determined as:

$$T = \Phi \times I_R \times \cos\varphi$$

where

Φ is the stator flux,
I_R is the rotor current
and
φ is the angle between Φ and I_R.

The rotor reactance varies with the rate of cutting flux, which depends on the rotor speed. Therefore, cosφ (power factor) will vary during motor startup as it accelerates up to its rated speed. If $\cos\varphi$ is ignored (for simplicity) then the shaft torque is approximately given by:

$$T = V^2 \text{ (as } \Phi = V \text{ and } I_R = \Phi)$$

The direction of the rotor torque causes the rotor to rotate in the same direction as the rotating magnetic field.

QUESTION

How is the rotor direction reversed?

ANSWER

Simply by swapping over any two supply line connections at the stator terminal box. This reverses the direction of the rotating magnetic field.

An induction motor cannot run normally at synchronous speed. This is because the rotor conductors would then be stationary with respect to the rotating magnetic field. No emf would be induced in the rotor and there would be no rotor current and no torque developed. Even when the motor is on no load, the rotor speed has to be slightly less than the synchronous speed (n_s) so that current can be induced into the rotor conductors to produce the torque to overcome the mechanical rotational losses of friction and windage.

Slip speed is the difference between the n_s of the rotating magnetic flux and actual rotor speed (n_R).

Slip is usually expressed as a percentage of the synchronous speed:

$$s = \left(\frac{n_s - n_R}{n_s}\right) \times 100\%$$

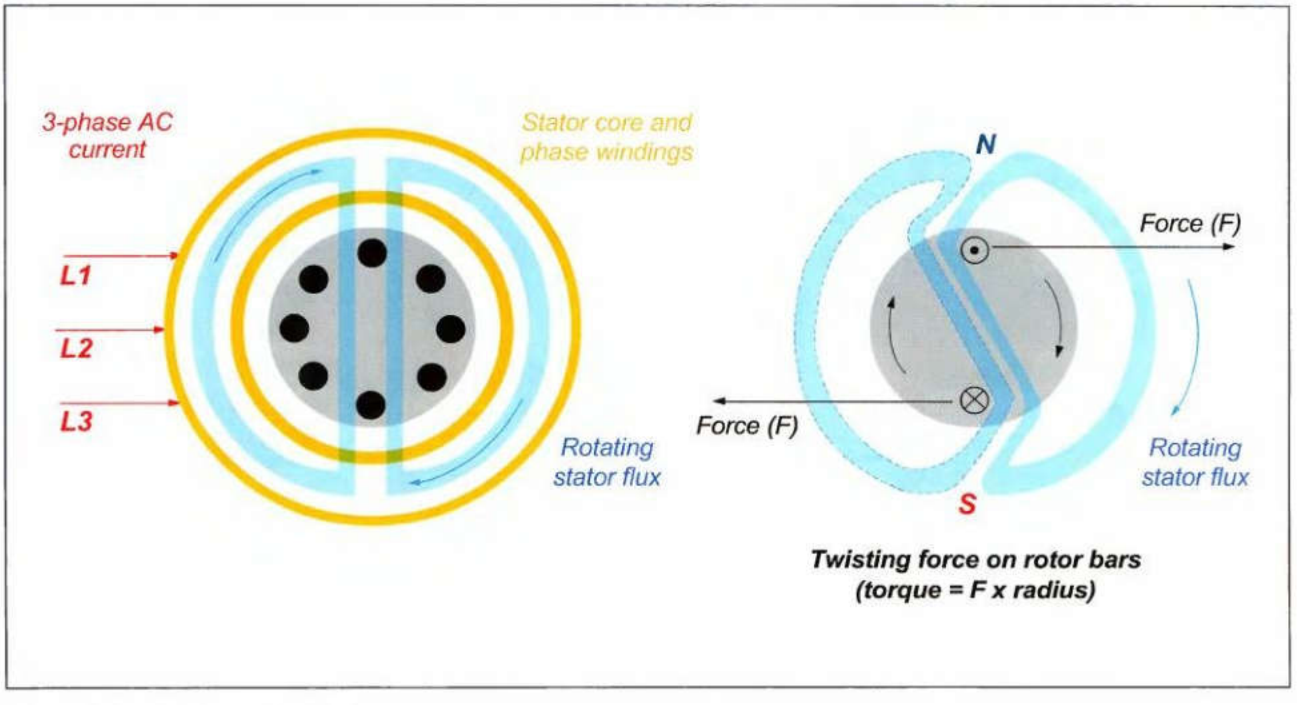


Figure 4.4 - Induction motor action

QUESTION

If a 6-pole motor is supplied at 60 Hz and runs with a slip of 5%, what is the actual rotor speed?

ANSWER

The synchronous speed is 1200 rpm, and the rotor slips by 5% of 1200, ie by 60 rpm so the rotor runs at 1140 rpm.

If the load torque on the motor shaft is increased, the rotor will tend to slow down (increasing the slip), which allows the rotor conductors to cut the flux at an increased rate. This causes more current to flow in the rotor, which is matched by more stator supply current to meet the increased shaft torque demand. The motor will now run at this new, slightly reduced, speed. The fall of motor speed between no load and full load is very small (between 1% and 5%), so induction motors are considered to be almost constant speed machines.

The characteristic in Figure 4.5 shows the variation of torque with slip for a standard cage-type induction motor. Also shown is a typical load characteristic that indicates the torque necessary to drive the load at different speeds.

At startup, the motor develops more torque than is necessary to turn the load, so the motor and load accelerate. The speed increases until, at the intersection of the two characteristics, the torque developed by the motor is the same as the torque required by the load at that speed. The motor and load will then run at this steady speed, as the torque supplied exactly matches the demand.

4.4 Control Equipment

When an induction motor is connected directly to its three-phase AC supply voltage, a very large stator current of 5-8 times full-load current (FLC) is taken. This is due to the maximum rate of flux cutting (s = 100%) in the rotor creating large induced rotor currents.

The corresponding supply power factor at startup is very low, typically about 0.2 lagging, which rises to about 0.5 lagging on no load then to about 0.85 lagging on full load.

This starting surge current reduces as the motor accelerates up to its running speed.

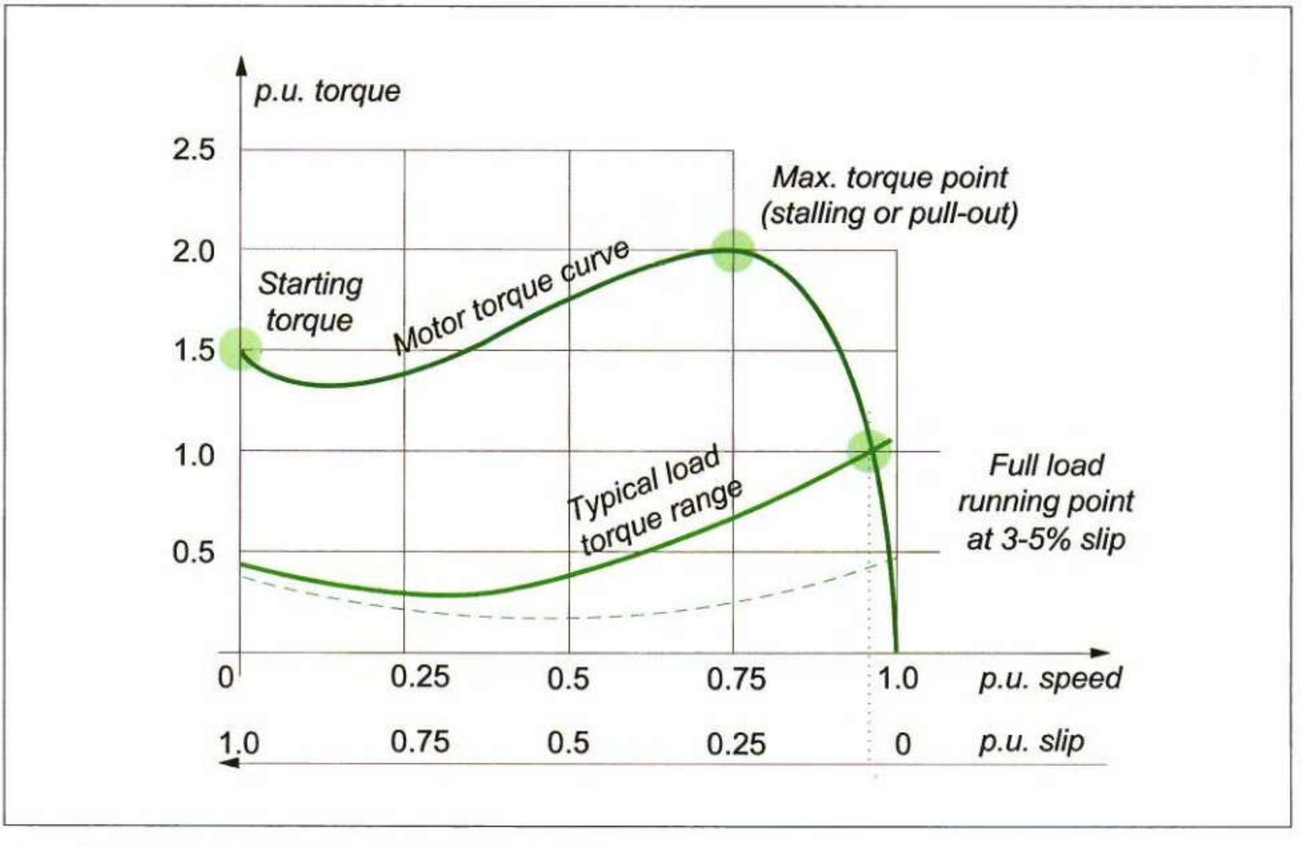


Figure 4.5 - Motor torque/speed curve and shaft loading

Operating on light loads at low power factor is inefficient as the supply current is relatively high, causing significant I^2R resistive (copper) losses. The only way to improve the power factor of the motor on light loads is to reduce the supply voltage. This can be achieved with an electronic voltage controller, called a soft starter and/or energy manager, which can match the supply voltage to the startup and load conditions. Such a controller aims to maintain the operating power factor as high as possible to minimise supply current and power losses.

Note: This type of *voltage* controller does not control shaft speed (which is controlled by *frequency*).

Relatively small size induction motors (up to 20 kW if the power from the main switchboard is sufficient) are direct on line (DOL) started because such starters are inexpensive and simple to operate and maintain. The high starting current surge will not cause serious heating damage to the motor unless the motor is repeatedly started and stopped in a short time period.

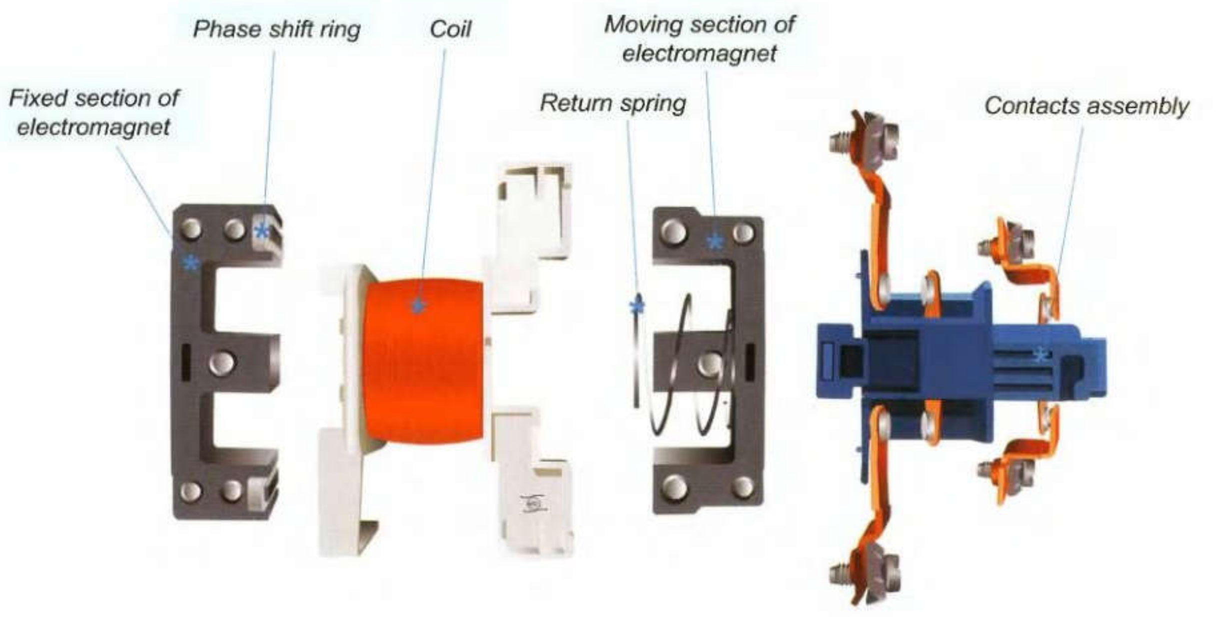
When large motors (20 kW and over) are started DOL, they cause a significant disturbance of voltage (voltage dip) on the supply lines due to the large starting current surge. This voltage disturbance may result in the malfunction of other electrical equipment connected to the supply, eg lighting dip and flickering effects, and even cause tripping of unessential consumers by means of undervoltage releases.

To limit the starting current, large induction motors (eg bow thrusters, cargo gears, etc) are started at reduced voltage and then have the full supply voltage reconnected when they have accelerated close to their rated speeds.

Two methods of reduced voltage starting by switching are called star-delta starting and autotransformer starting, but an electronic 'soft' starting option is also used.

Contactors, as shown in Figure 4.6, perform the switching action in starters to connect and disconnect the power supply to the motor.

The contactor is an electromagnetically-operated three-pole switch initiated from local and/or remote stop/start push buttons. If the current goes above the rated current for the motor, its contactor will be tripped out automatically by an overcurrent relay (OCR) to disconnect the motor from the supply (see Section 4.8).



Telemecanique LC1D contactor internal components

Figure 4.6 - Contactor construction

4.5 Direct on Line (DOL) Starting

In the example circuit shown in Figure 4.7, the induction motor is directly switched onto the three-phase AC power supply lines by means of contactor –KM1. This is a very simple starting arrangement that is used for the majority of small sized induction motor drives.

The switching sequence for this starter circuit is as follows:

Power circuit operation

- Manual closing of motor starter protector –Q1
- closing of main contactor –KM1. –KM1 contactor 'holds-in'
- –KM1 contactor drops out, motor stops.

Control circuit operation

- Control circuit voltage available (eg 24 V from control transformer) after closing –F2 miniature circuit breaker
- press start button –S1
- auxiliary contact 13-14 of –KM1 'latches' contactor
- remote indicator lamp –H1 'on'
- press stop button –S2
- on overload, the OCR –F1 trips out the NC contact 95-96 (to start motor again, –F1 should be reset by hand after the internal heater's cooling down time).

Further circuit additions can be made for remote and automatic control (by pilot switches, eg by liquid level switch, pressure switch, limit switch, etc) and motor reversing (with an extra contactor).

DOL switching demands a short duration but large starting current of 5-7 times FLC fixed by the motor impedance and is generally acceptable to the supply generator as long as the corresponding voltage dip is not greater than 10-15% within the run-up period. For large motor drives, this starting surge will cause an unacceptable voltage dip at the supply busbars, with likely malfunctions of other consumers, eg lighting flicker and possible drop out of unessential consumers' circuit breakers due to tripping of undervoltage releases. The voltage dip is further compounded as all the other connected motors compensate by demanding an increased current to maintain their original power output. If prolonged, this sudden current loading may cause supply line and generator protection to trip.

This is the reason why large motors (eg bow and stern thrusters, cargo gears, ballast and fire

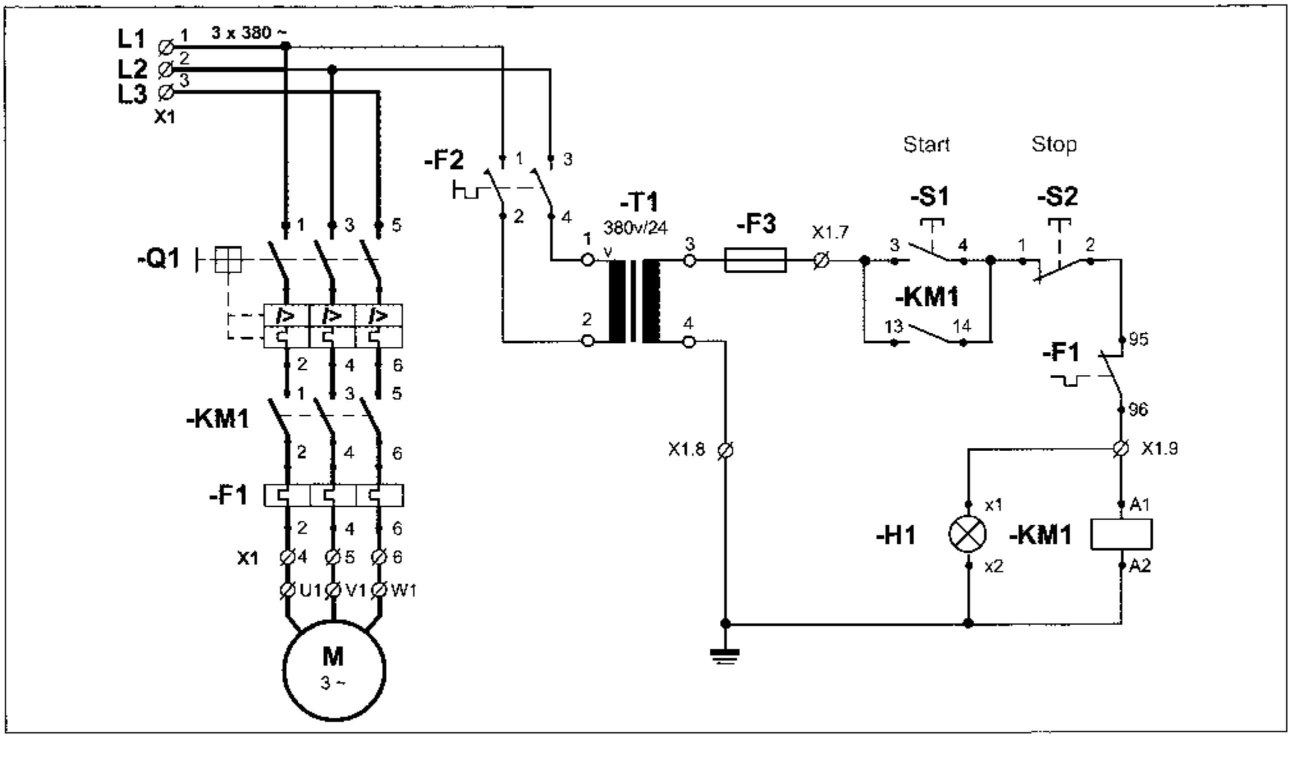


Figure 4.7 - DOL starter circuit

pumps, etc) require a more complicated starting method to limit the size of starting current and protect the generator supply and other consumers. This means applying a reduced voltage at startup.

4.6 Reduced Voltage Starting

During the run-up period, the size of motor starting current can be limited either by applying a reduced supply voltage or by inserting some additional circuit impedance. The most common arrangement is to apply reduced voltage, which is sub-divided into the methods of star-delta switching, auto-transformer starting and 'soft' starting.

Star-delta starting

If a motor is DOL started with the stator winding star connected, it will only take one third of the starting current that it would take if the windings were delta connected. The starting current of a motor that is designed to run delta connected can be reduced in this way.

Star-delta starters for small motors may be operated by a manual changeover switch. For large power motors, the phase windings are automatically switched using contactors controlled by a timing relay, as shown in Figure 4.8. A variety of pneumatic, electronic and solid state time relays are available from manufacturers.

The switching sequence for this starter circuit:

Power circuit operation

- Manual closing of fused-isolator –Q1
- closing of contactor –KM1: neutral contactor
- closing of –KM2: star contactor
- opening of –KM2: star connection opens
- closing of –KM3: delta contactor
- –KM1, –KM3 contactors drop out, motor stops.

Control circuit operation

- Control circuit voltage available (eg 24 V from control transformer) after closing –F2 miniature circuit breaker
- press start button –S1 to close –KM1; –KM1 holds in; –KM2 closes interlocking –KM3 (–KM2 NC contacts 21-22 open)
- time relay –KT1 energises and begins to count down preset time delay
- –KT1 time delay elapsed, –KM2 de-energises by –KT1
  (NC contacts 15-16 open); –KM2 interlocking contacts 21-22 close
- closing of –KM3 by –KT1 (NO contacts 15-18 close); –KM3 interlocking contacts 21-22 open
- stop by S2 button or OCR trip F1: –KM1, –KM3 de-energises; –KM3 interlocking contacts 21-22 close.

Note: time relay –KT1 is usually set for a 5-9 second time gap depending on the size of motor.

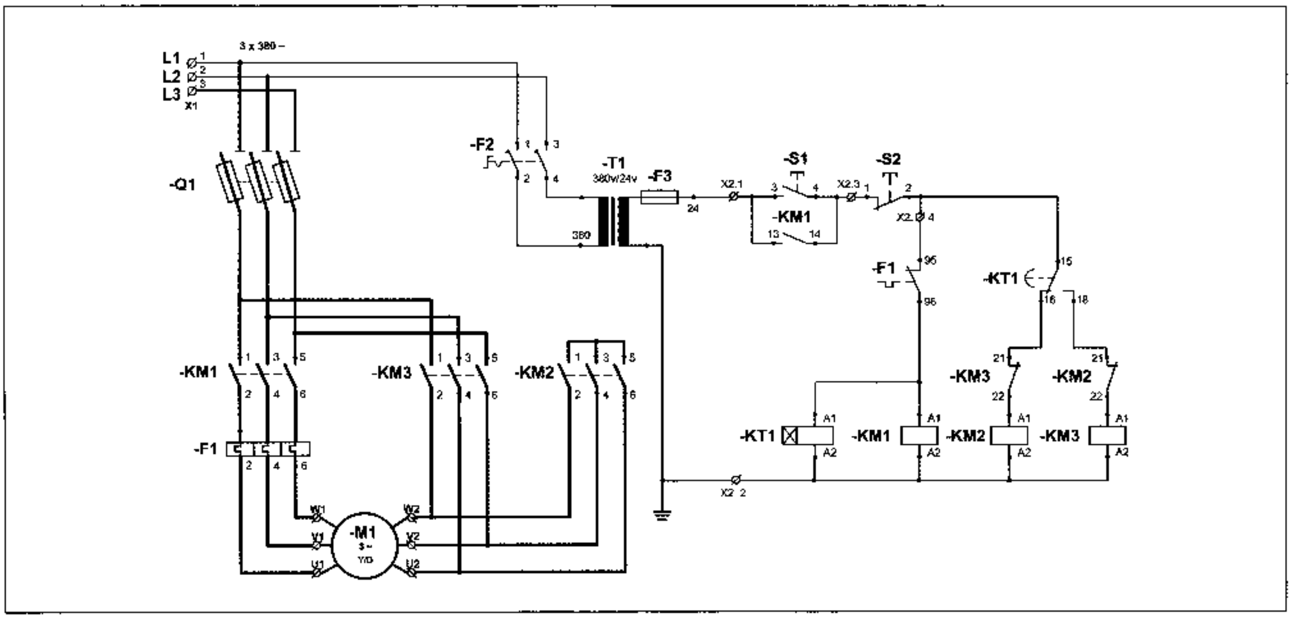


Figure 4.8 - Star-delta motor starter diagram

QUESTION

Why are the interlocking contacts of –KM2 and –KM3 necessary?

ANSWER

This is to prevent a full *short-circuit* fault across the supply lines during the changeover from *star* to *delta*.

At the instant of starting, when the supply has just been switched on and the motor has not yet started to rotate, there is no mechanical output from the motor. The only factors that determine the current taken by the motor are the supply voltage (V) and the impedance of the motor phase windings (Z_{PH}).

Compare the starting current when star connected to the starting current when delta connected, as in Figure 4.9.

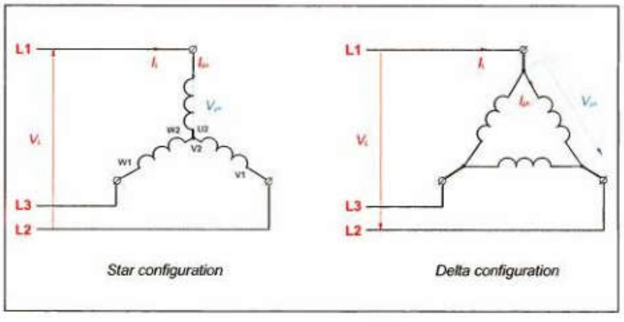


Figure 4.9 - Star-delta connections

$$\text{ratio of: } \frac{I_{L(Y)}}{I_{L(\Delta)}} = \frac{V_L / \sqrt{3} \times Z}{\sqrt{3} \times V_L / Z} = \frac{1}{3}$$

This shows that the starting current of a delta connected motor can be reduced to one third if the motor is star connected for starting. The shaft torque is also reduced to one third, which reduces the shaft acceleration and increases the run-up time for the drive, although this is not usually a problem.

When an induction motor is running on load, it converts electrical energy input to mechanical energy output. The input current is determined by the load on the motor shaft.

An induction motor will run at the same speed when it is star connected as when it is delta connected because the flux speed is the same in both cases (being set by the supply frequency).

This means that the power output from the motor is the same when the motor is star connected as when the motor is delta connected, so the power inputs and line currents must be the same when running in either connection.

If the motor is designed to run in delta (for the line voltage of 440 V) but is run as star connected, and on full load, then each stator phase winding will be carrying an overcurrent of √3 times rated phase current. This is because phase and line currents are equal in a star connection.

This will cause overheating and eventual burnout unless tripped by the overcurrent relay. Remember that the motor copper losses are produced by the I^2R heating effect, so the motor will run $(\sqrt{3})^2 = 3$ times hotter if left to run in the *star* connection when designed for *delta* running. This malfunction may occur if the control timing sequence is not completed or the *star* contactor remains closed while a mechanical interlock prevents the *delta* contactor from closing.

For correct overcurrent protection, the overcurrent relays must be fitted in the phase connections and not in the line connections.

Autotransformer starting

Starting a large motor with a long run-up period will demand a very high current surge from the supply generator for a few seconds. This causes a severe voltage dip that affects every load on the system. Reduced voltage starting will limit the starting surge current.

One way to reduce the initial voltage supplied to the motor is to step it down using a transformer. Then, when the motor has accelerated up to almost full speed, the reduced voltage is replaced by the full mains voltage. The transformer used in this starter is not the usual type, with separate primary and secondary windings, but is an autotransformer that uses only one winding for both input and output. This arrangement is cheaper, smaller and lighter than an equivalent double wound transformer and it is only in operation during the short starting period. For induction motor starting, the autotransformer is a three-phase unit and, because of expense, this method is only used with large motor drives, eg electric cargo pumps.

Figure 4.10 shows that the supply voltage is connected across the complete winding and the motor is connected to the reduced voltage tapping. A number of tappings are usually available on

QUESTION

What causes the large current surge in open transition starters when going from the start to the run condition?

ANSWER

All motors generate a back emf against the supply voltage when they are running. When the supply is removed from a running induction motor, the magnetic field does not immediately collapse. The motor begins to slow down but still generates an emf. When reconnected in open transition, the supply voltage and motor emf are not necessarily in phase (the condition is similar to synchronising a generator onto the busbars). An additional current surge is, therefore, likely at the changeover stage, causing further voltage dip and so affecting other consumers. Closed transition starters overcome this because the motor is never actually disconnected from the supply during the starting cycle. Most autotransformer starters used the closed transition method.

the transformer winding, giving voltage outputs ranging from about 50% to 80% of the mains supply voltage. For example, a 60% tap on an autotransformer supplied at 440 V would provide a voltage output of 60% of 440 = 264 V.

The autotransformer usually has a few tapping points to give a set of reduced voltages (eg 40%, 50% and 65%), which helps to match the motor current demand to the supply capability.

As with the star-delta starter, the autotransformer may use what is called an open transition switching sequence or a closed transition switching sequence between the start and run conditions. In open transition, the reduced voltage is supplied to the motor at start, then disconnected and the full supply voltage rapidly reconnected to the motor.

The problem with *open transition* is that a large enough surge current can flow after the transition from reduced to full voltage.

A typical autotransformer starter circuit is shown in Figure 4.11.

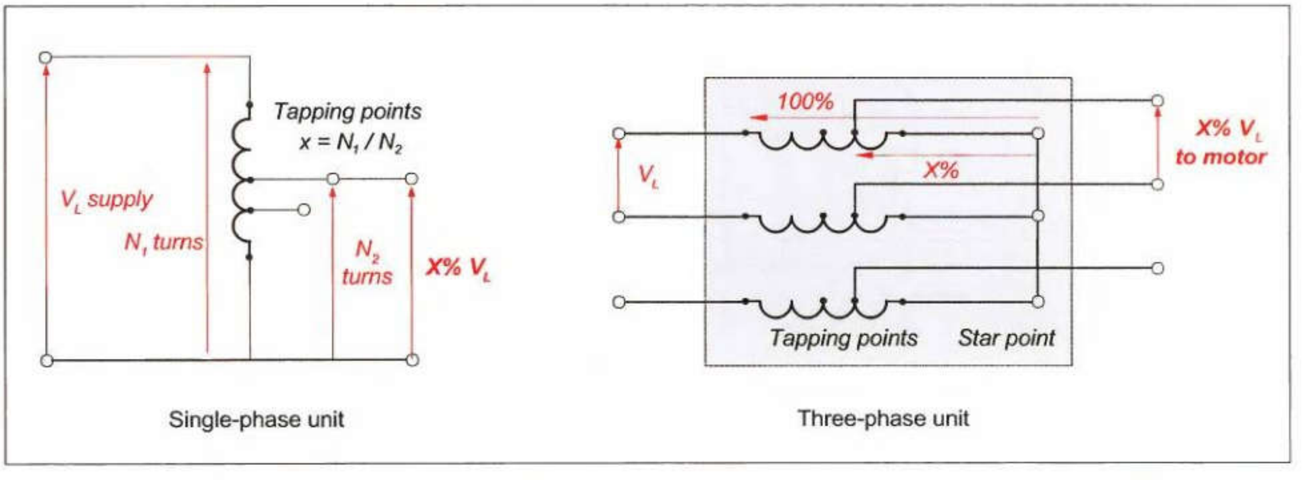


Figure 4.10 - Autotransformer connections

The switching sequence for this starter circuit is as follows:

Power circuit operation

- Manual closing of fused-isolator –Q1
- closing –KM1: star connection of transformer
- closing of –KM3: motor supply via transformer
- opening of –KM1: star connection opens closing of –KM2: direct supply to motor (Note the electrical interlock of KM1–KM2)
- –KM2 contactors drop out, motor stops.

Control circuit operation

- Manual closing of miniature circuit breaker –F2; control circuit voltage available (eg 24 V from –T1)
- press start button S1 to energise –KM1, which holds in by –KM1/13-14
- energising –K1 control relay with top mounted pneumatic On-delay time module
- energising of –KM3 via closed –KM1/43-44
- interlocking of –KM2 by –KM1/21-22
- de-energising of –KM1 by opened –K1/55-56 (after time delay has elapsed)
- de-energising –KM3 by opened –KM1/43-44
- closing interlocking contact –KM1/21-22
- energising –KM2 by closed K1/67-68
- interlocking of –KM1 by –KM2/21-22
- de-energising of –KM2 by stop button –S2 or OCR trip (–F1).

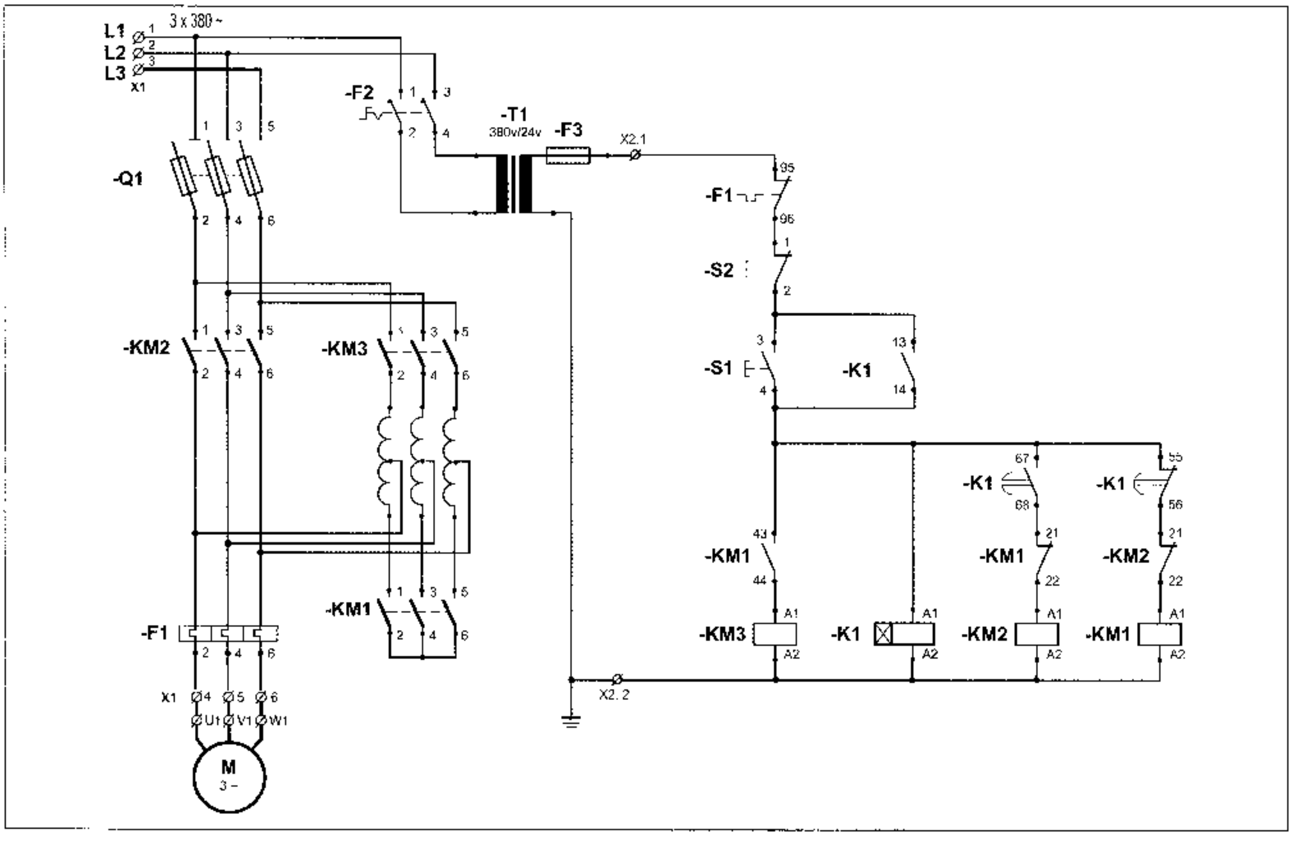


Figure 4.11 - Autotransformer motor starter

'Soft' starting

This method of supplying a gradually increasing AC voltage during startup generally refers to an efficient electronic switching technique.

A basic method, shown in Figure 4.12, is to use back to back connected thyristors or triacs in the supply lines which are gated to delay turn-on within each AC half cycle. This delayed switching applies a reduced average AC voltage to the motor.

The applied motor voltage is gradually ramped up by the starter software program until the full voltage level is reached. To achieve maximum efficiency, the electronic switching circuit can now be bypassed for normal running.

A soft starter may be further adapted to become a voltage controller over the motor operating load range. In this type of efficient energy manager application, the controller monitors the motor power factor, which is a measure of the motor loading. On light load and full voltage, the power factor is low so the controller reduces the motor voltage, which reduces current while improving power factor and efficiency.

Note that this type of soft-start/energy manager is not a speed controller. To electrically change the speed of an induction motor it is necessary to vary the applied frequency. Motor speed control methods are outlined in Section 4.7.

QUESTION

Estimate and compare the likely starting current surges for a motor that takes 200 A on full load when started:

(a) DOL

(b) Star Delta

(c) Autotransformer with a 50% tapping.

ANSWER

(a) When starting DOL, the initial surge current is about 5 × *FLC,* ie 1000 A.

(b) A star-delta starter reduces the initial starting surge to one-third of the equivalent DOL value, ie to about 330 A in this case.

(c) The autotransformer method reduces the initial starting surge to $(x)^2 \times I_{DOL}$ where x = tapping point.

In this example, $x = 0.5$, so the surge current level is $0.5^2 \times 1000 = 250$ A.

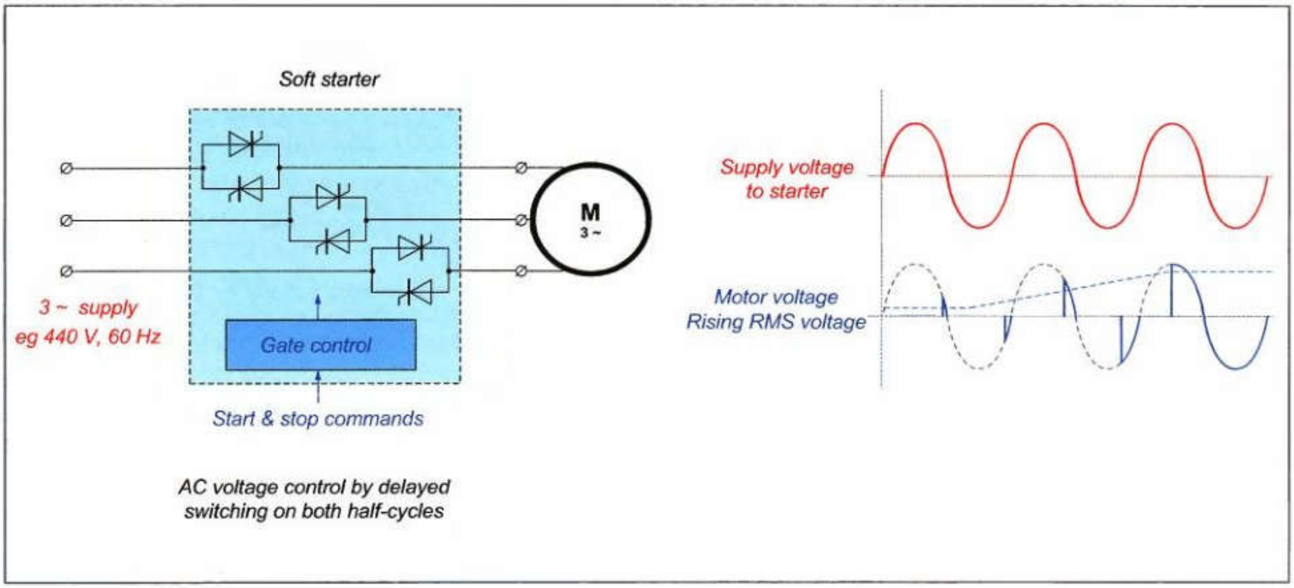


Figure 4.12 - 'Soft' starter block diagram

4.7 Speed Control

The standard cage rotor AC induction motor operates as an almost constant speed drive over its load range. This feature is satisfactory for most of the ship's auxiliary services, such as those supplying power to ventilation fans and circulating pumps.

Variable speed control is necessary for cranes, winches, windlass, capstans, forced draught fans, etc. A ship's electric propulsion with electronic speed control may use DC motors or AC induction motors for low/medium power applications. Large power electric propulsion, eg for a passenger cruise ship, will use AC synchronous motors (see Chapter 8).

Two main forms of speed change/control are available:

- Pole-changing for induction motors to give two or more fixed speeds, eg 2-speed forced-draught fans and 3-speed winches
- continuously variable speed control, eg smooth control of winches and electric ship propulsion using variable frequency.

Fixed set speeds can be obtained from a cage rotor induction motor by using a dual wound stator winding, each winding being designed to create a different number of magnetic poles.

A 3-speed pole change winch motor can be arranged by having three stator windings. One stator winding (usually 24-pole) gives a low speed, while the other is dual wound to give medium speed (8-pole) and high speed (4-pole) outputs.

Speed control and drive direction are achieved by a set of switching and reversing contactors operated from the winch control pedestal.

Remember that to reverse the rotation of an induction motor it is necessary to switch over two of the supply lines to the stator winding.

An alternate method, giving two fixed speeds in a 2:1 ratio from a cage rotor induction motor, is to use a single stator winding that has centre-tap connections available on each phase. This method uses a starter with a set of contactors to switch the phase windings into either single star (low speed)

QUESTION

A dual wound induction motor is arranged to create 4-pole and 8-pole stator magnetic fields. Estimate the rated speeds assuming that the rotor slips by 5% and the power supply is at a frequency of 60 Hz.

ANSWER

At high speed (4-pole, p = 2),
$n_s = 60/2 = 30$ *rev/s or 1800 rpm*
but rotor runs at
$n_R = 95\% \times 12/100 = 28.5$ *rev/s or 1710 rpm.*

At low speed (8-poles, p = 4),
$n_s = 60/4 = 15$ *rev/s or 900 rpm*
but rotor runs at
$n_R = 95\% \times 15/100 = 14.25$ *rev/s or 855 rpm.*

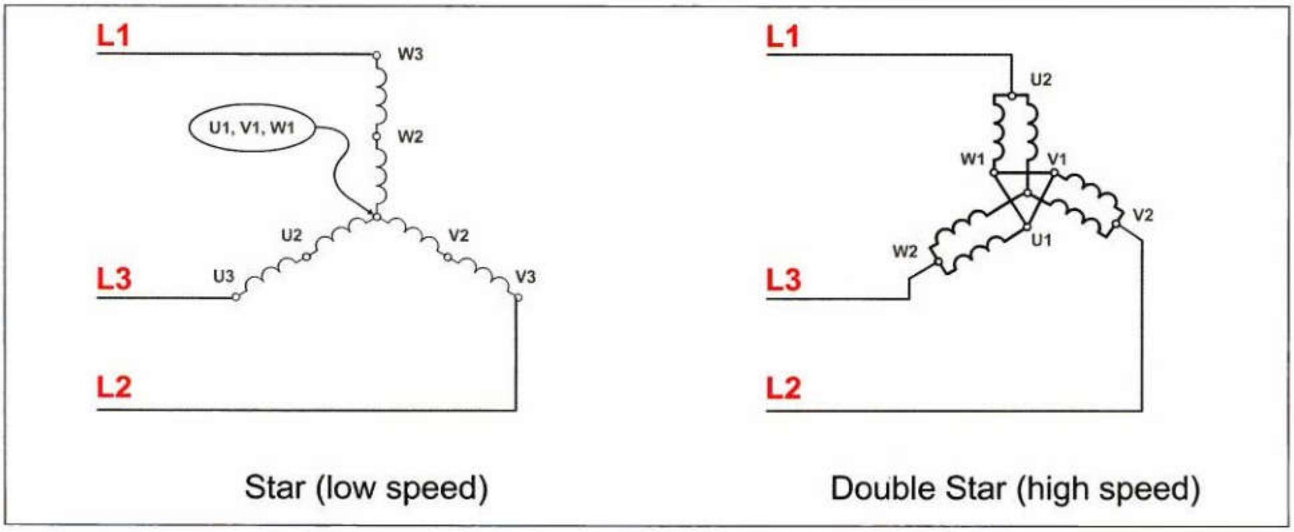


Figure 4.13 - Star-double star connections

or double-star (high speed). The supply lines to the stator windings are shown in Figure 4.13.

A continuously variable speed range of motor control involves more complication and expense than that required to obtain a couple of set speeds. Various methods are available, including:

- Electrohydraulic drive
- wound rotor resistance control of induction motors
- Ward-Leonard DC motor drive
- variable frequency induction or synchronous motor control.

The electrohydraulic drive, often used for deck crane control, has a relatively simple electrical section. This is a constant single speed induction motor supplied from a DOL or star-delta starter. The motor runs continuously to maintain oil pressure to the variable speed hydraulic motors.

A crude form of speed control is provided by the wound rotor induction motor. The rotor has a three-phase winding (similar to its stator winding) which is connected to three slip rings mounted on the shaft, as shown in Figure 4.14. An external three-phase resistor bank is connected to brushes on the rotor slip rings. During motor start up, a set of large size contactors varies the amount of resistance added to the rotor circuit.

Increasing the value of external resistance decreases the rotor speed. This has the benefits of reducing the starting current surge while providing a high starting torque.

The wound rotor arrangement is more expensive than an equivalent cage rotor machine. It requires more maintenance on account of the slip rings and the external resistor bank, which may require additional cooling facilities (eg forced cooling by a fan situated beneath the bank and compulsory air extraction from the bow thruster room).

Where continuously variable speed has to be combined with high torque and smooth acceleration, including inching control and regenerative braking, it is necessary to consider the merits of a DC motor drive. Speed and torque control of a DC motor requires only the variation of armature voltage and field current.

The problem is: where does the necessary DC power supply come from on a ship with an AC electrical system?

A traditional method for lifts, cranes and winches is found in the Ward-Leonard drive, as shown in Figure 4.15. Here, a constant speed induction motor drives a DC generator which, in turn, supplies one or more DC motors. The generator output voltage is controlled by adjusting its small excitation current via the speed regulator. The DC motor speed is directly controlled by the generator voltage.

The motor generator (M-G) set requires space and maintenance. An alternative is to replace the rotary M-G set with a static electronic thyristor controller, which is supplied with constant AC voltage but delivers a variable DC output voltage to the drive motor, as shown in Figure 4.16.

Although the Ward-Leonard scheme provides an excellent power drive, practical commutators are limited to about 750 V DC maximum, which also limits the upper power range. The commutators on the DC machines also demand an increased maintenance requirement.

To eliminate these problems means returning to the simplicity of the cage rotor induction motor.

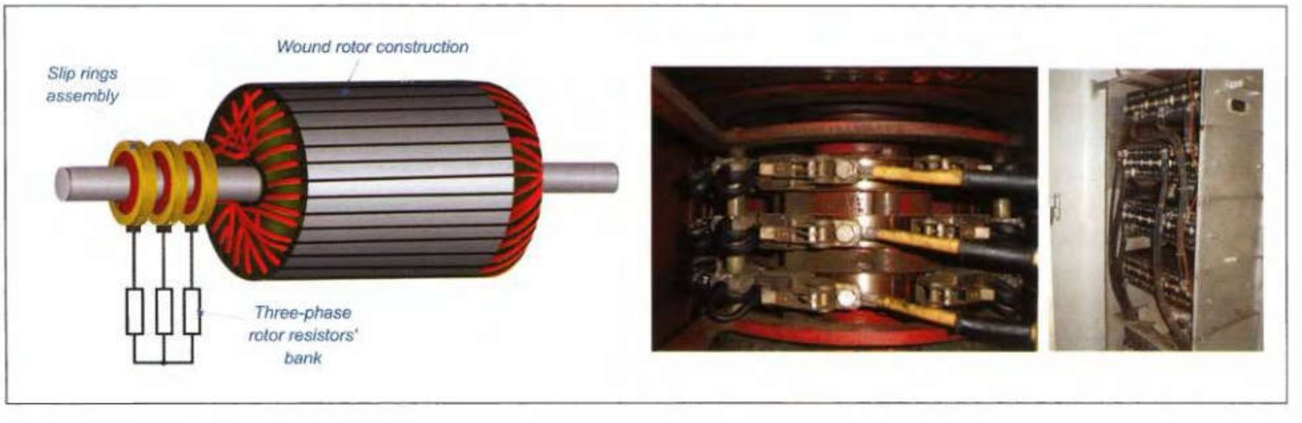


Figure 4.14 - Wound rotor construction

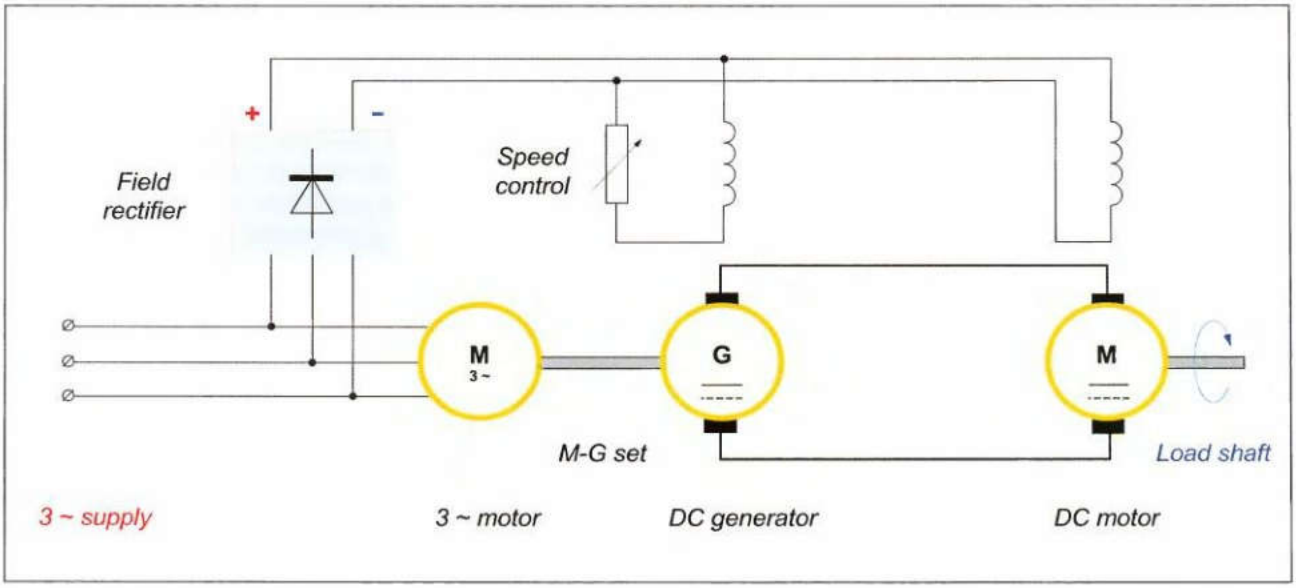


Figure 4.15 - Ward-Leonard speed control method

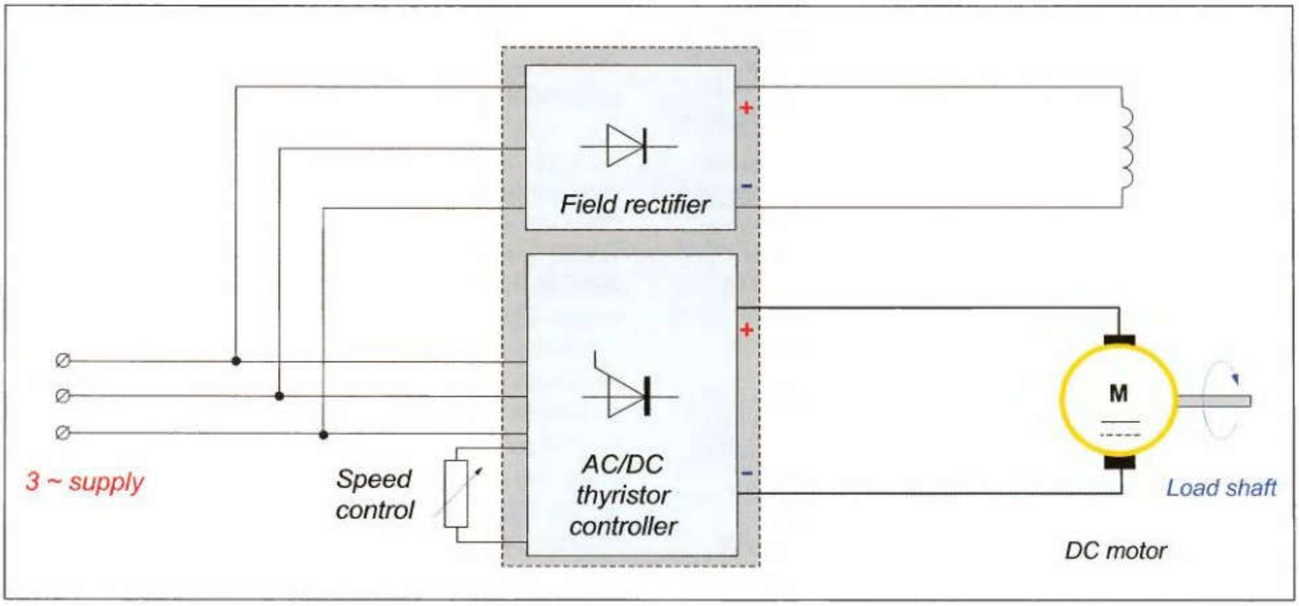


Figure 4.16 - Electronic control for a DC motor

However, the only way to achieve a continuously variable speed output by electrical control is to vary the supply frequency to the motor. A static electronic transistor or thyristor (high power) controller can be used to generate such a variable frequency output to directly control the speed of the motor, as shown in Figure 4.17.

In an electronic variable speed drive (VSD), the fixed AC input is rectified and smoothed by a capacitor to a steady DC link voltage (about 600 V DC from a 440 V rms AC supply). The DC voltage is then chopped into variable width, but constant level, voltage pulses in the computer-controlled inverter section using insulated gate bipolar transistors (IGBTs). This process is called pulse width modulation or PWM (see Figure 4.18). By varying the pulse widths and polarity of the DC voltage, it is possible to generate an averaged sinusoidal AC output over a wide range of frequencies. Due to the smoothing effect of the motor inductance, the motor currents appear to be approximately sinusoidal in shape. By directing the currents in sequence into the three stator winding, a reversible rotating magnetic field is produced at a frequency set by the PWM modulator.

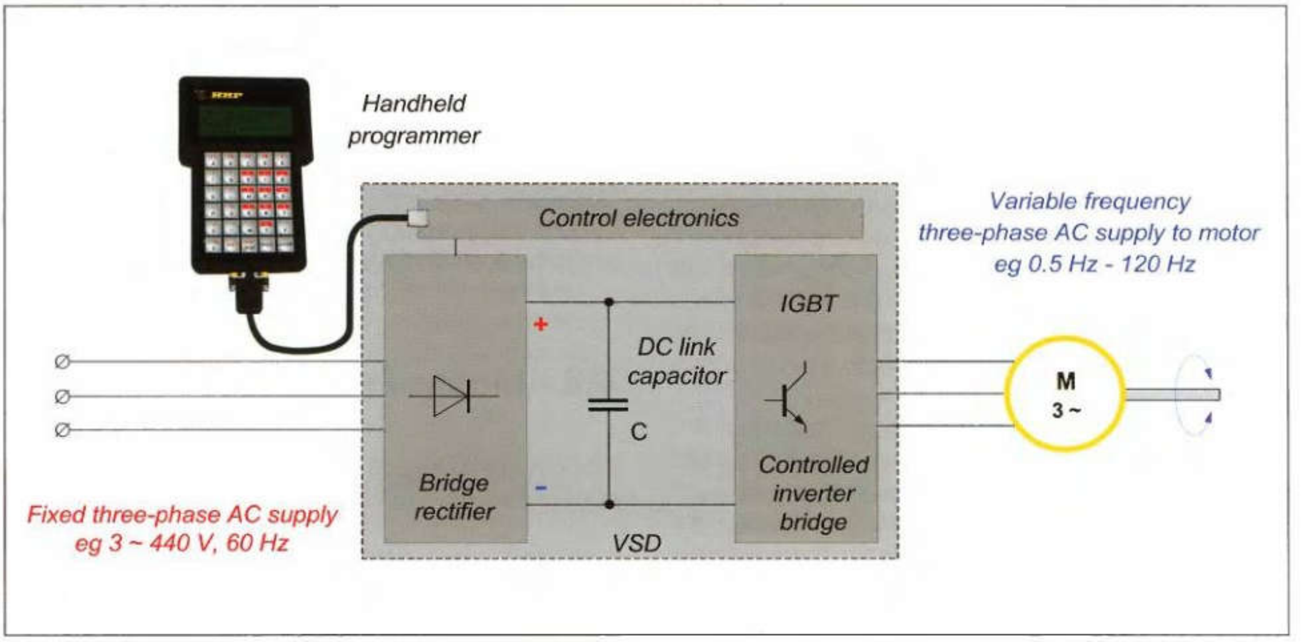


Figure 4.17 - Electronic VSD controller

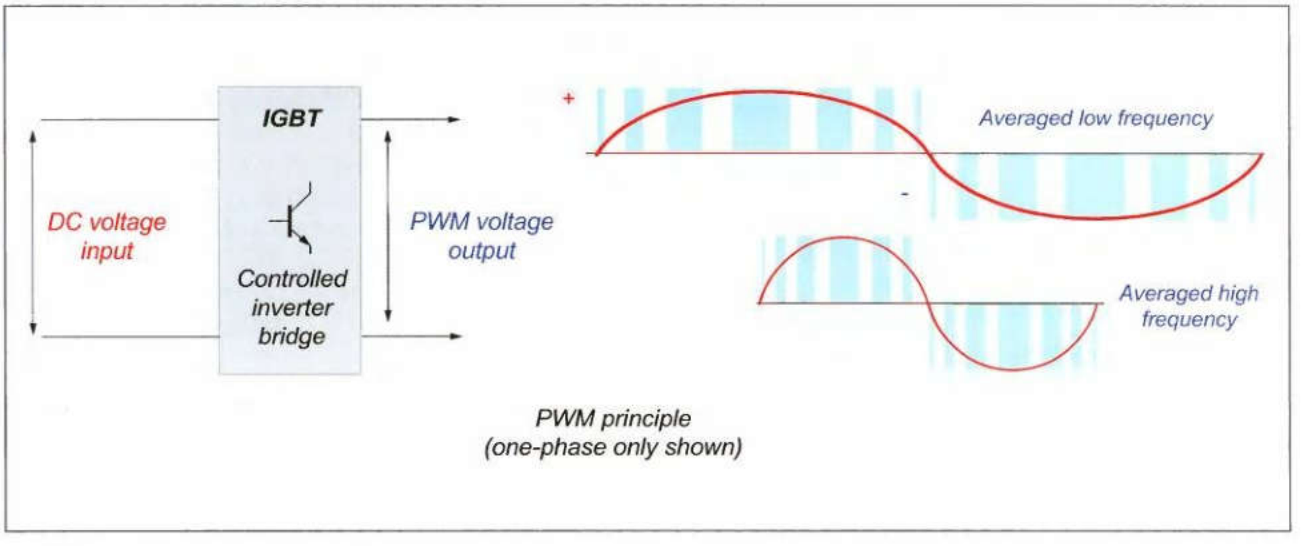


Figure 4.18 - PWM control method

Accurate control of shaft torque, acceleration time and braking are a few of the many operational parameters that can be programmed into the VSD, usually via a handheld unit. The VSD can be closely tuned to the connected motor drive to achieve optimum control and protection features for the overall drive. Speed regulation against load changes is very good and can be made precise by the addition of feedback from a shaft speed encoder.

VSDs, being digitally controlled, can be easily networked to other computer devices, eg programmable logic controllers (PLCs), for the overall control of a complex process.

A disadvantage of chopping large currents with such a drive is that it creates harmonic voltages back into the power supply network. A harmonic voltage waveform is a distorted sinusoidal waveshape.

The analysis (not covered here) of a distorted waveshape reveals a set of sinusoidal harmonic voltages superimposed upon the base (or fundamental) frequency. Harmonic frequencies are integer (whole number) multiples of the fundamental frequency. In an AC system, even numbered harmonics are conveniently self-cancelling, as are multiples of three in a three-phase network. This leaves harmonic numbered frequencies of 5, 7, 11, 13, 17, 19, etc. Fortunately, the higher the harmonic number, the lower the amplitude of the harmonic voltage. For a 60 Hz fundamental (1st harmonic), a 5th harmonic would be at a frequency of 300 Hz and a 7th harmonic would be at 420 Hz. The amplitude of a 5th harmonic may be up to about 20% of the fundamental while the 7th will be down to about 14% and so on.

Such harmonic voltage disturbances caused by current switching can interfere with other equipment connected to the power system, resulting in, for example, progressive insulation breakdown due to high voltage spikes, flickering of the lighting and malfunction of low current devices such as electronic computers and instrumentation/ control circuits.

Minimising harmonic disturbance involves good circuit design and the fitting of harmonic filters adjacent to the VSD drive. A harmonic filter is a combination of inductance and capacitance units tuned to absorb the unwanted frequencies.

Be guided by the manufacturer's installation notes regarding the need for filters, acceptable cable rating and length, earthing and bonding etc, before fitting such a drive.

Very large drives use thyristor converters and synchronous motors, eg for ship's electric propulsion, as outlined in Chapter 8.

4.8 Motor Protection

The circuits in Figure 4.19 show typical motor control circuits on LV and HV supplies.

In the HV motor protection scheme, the backup fuses are the trigger type. This type of fuse releases a trigger actuated by a spring held in tension until the element melts. When released, the trigger may be used to indicate a blown fuse or to trip a circuit breaker or contactor. Trigger fuses are an additional protection against a single phasing fault, so that the motor is definitely tripped out when a single fuse blows.

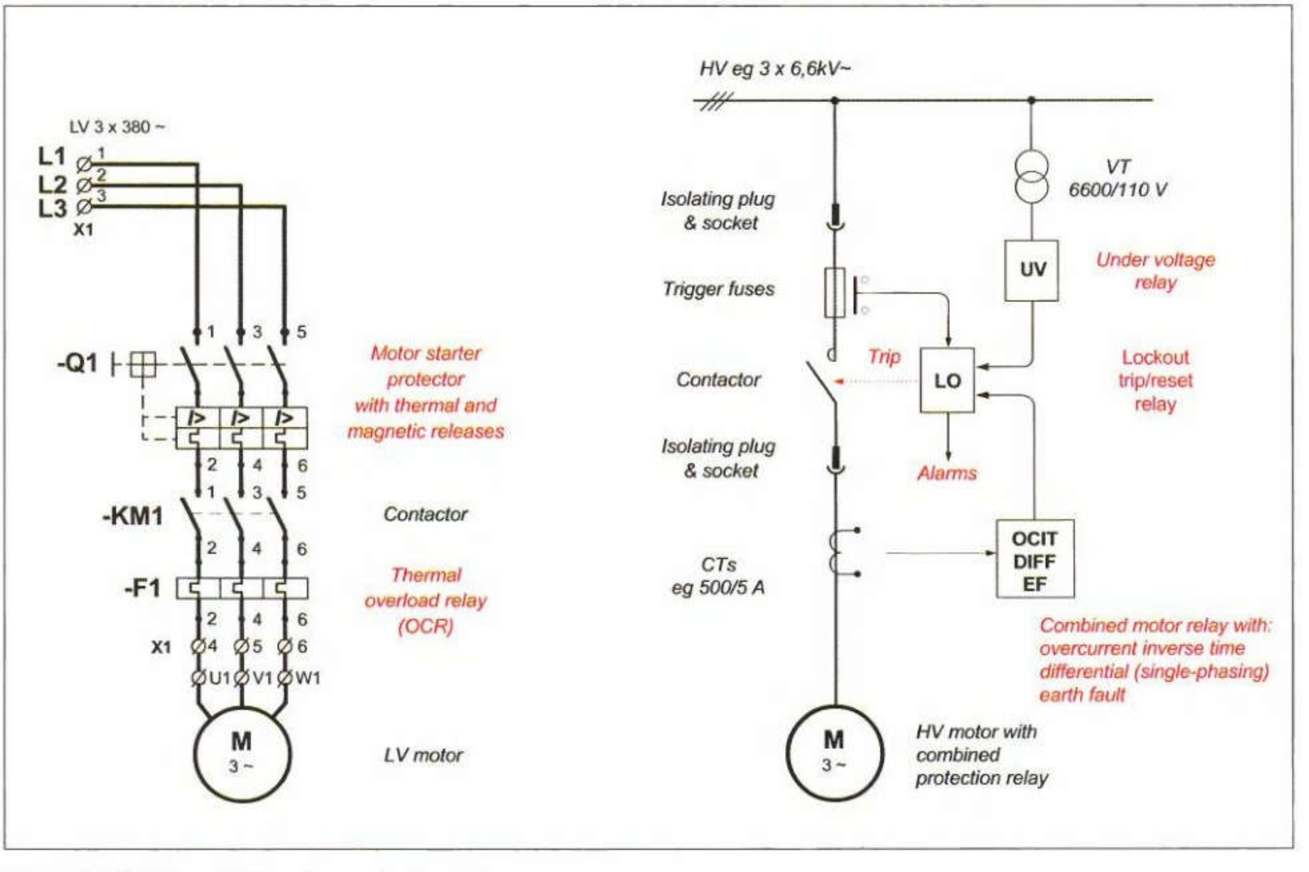


Figure 4.19 - LV and HV motor protection scheme

To protect an electric motor it must be prevented from getting too hot.

> Remember, every 10°C above the maximum recommended temperature of the insulation can reduce its working life by half.

The best way to protect a motor against overheating is to directly monitor the temperature of the motor windings. If the temperature exceeds the maximum set value for the motor insulation, its contactor is tripped to stop the motor and allow it to cool down.

Three main types of direct temperature sensors can be used. These are:

- Thermocouple
- resistance temperature device (RTD)
- thermistor.

The thermistor sensor is probably the most common as its thermal characteristic more closely matches that of a motor than the other types. Thermistors are small pellets of semiconductor material that are embedded upon the insulation of all three-phase stator windings during manufacture. When a thermistor gets hot its resistance changes dramatically. They are connected so that if the motor temperature gets too high the starter contactor will be tripped, by an electronic protection relay, to stop the motor.

Direct thermistor protection is usually only fitted to large motors, eg bow thrusters, FD fans, air conditioning compressors, etc.

Most motors are protected by monitoring the temperature indirectly by measuring the current flowing in the supply lines. This method uses electronic, thermal or electromagnetic time-delayed overcurrent relays (OCRs) in the motor starter. The system is designed so that if the motor takes too much current as a result of being mechanically overloaded, the OCR will trip out the contactor coil, after a pre-set time delay, before severe overheating can occur.

The largest overcurrent possible is the current taken when the motor has stalled. This is the starting current of the motor, which will be about five times the full load current. The contactor is capable of tripping this stalled current quickly and safely.

If a short-circuit occurs in the motor, the starter or the supply cable, then a huge fault current will flow. If the contactor tries to open under short-circuit conditions, serious arcing will occur at its contacts and it may fail to interrupt the fault current. The prolonged short-circuit current will cause serious damage to the motor, starter and cable, with an attendant risk of an electrical fire. To prevent this a set of fuses, or a circuit breaker, is fitted upstream of the contactor. This will trip out almost instantaneously, thereby protecting the contactor during a short-circuit fault.

It is important that the tripping characteristics, as shown in Figure 4.20, of the OCR and fuses/circuit breaker are coordinated so that the contactor trips on thermal overcurrent while the fuses/circuit breaker interrupt short-circuit fault currents. This contactor and fuse arrangement is usually called backup protection.

It must be emphasised that the motor fuses are not chosen for their rated current but for their inverse current/time (I/t) characteristic. This means that the current rating of fuses used to protect a motor will not appear to have any direct relationship to the FLC rating of the motor.

QUESTION

At what value of current should the OCR be set?

ANSWER

To protect a modern continuous maximum rating (CMR) motor, the thermal OCR should be set at the full load current (FLC) rating of the motor. This will ensure that tripping will not occur within two hours at 105% FLC. At 120% FLC, tripping will occur within two hours.

Fuses used for backup protection of motor circuits have a special time/current characteristic. They are generally carrying steady currents well below their rated capacity to allow for short duration DOL starting currents without blowing. Consequently, they do not protect against normal overloads but do protect the motor and supply system against a short-circuit fault. Fuses designed for motor circuit backup protection have a restricted continuous current rating (called 'M' rating), which is different to their fusing characteristic.

A typical fuse designation for motor circuits could be '32M63', which indicates a continuous rating of 32 A, but a rating of 63 A for the starting period.

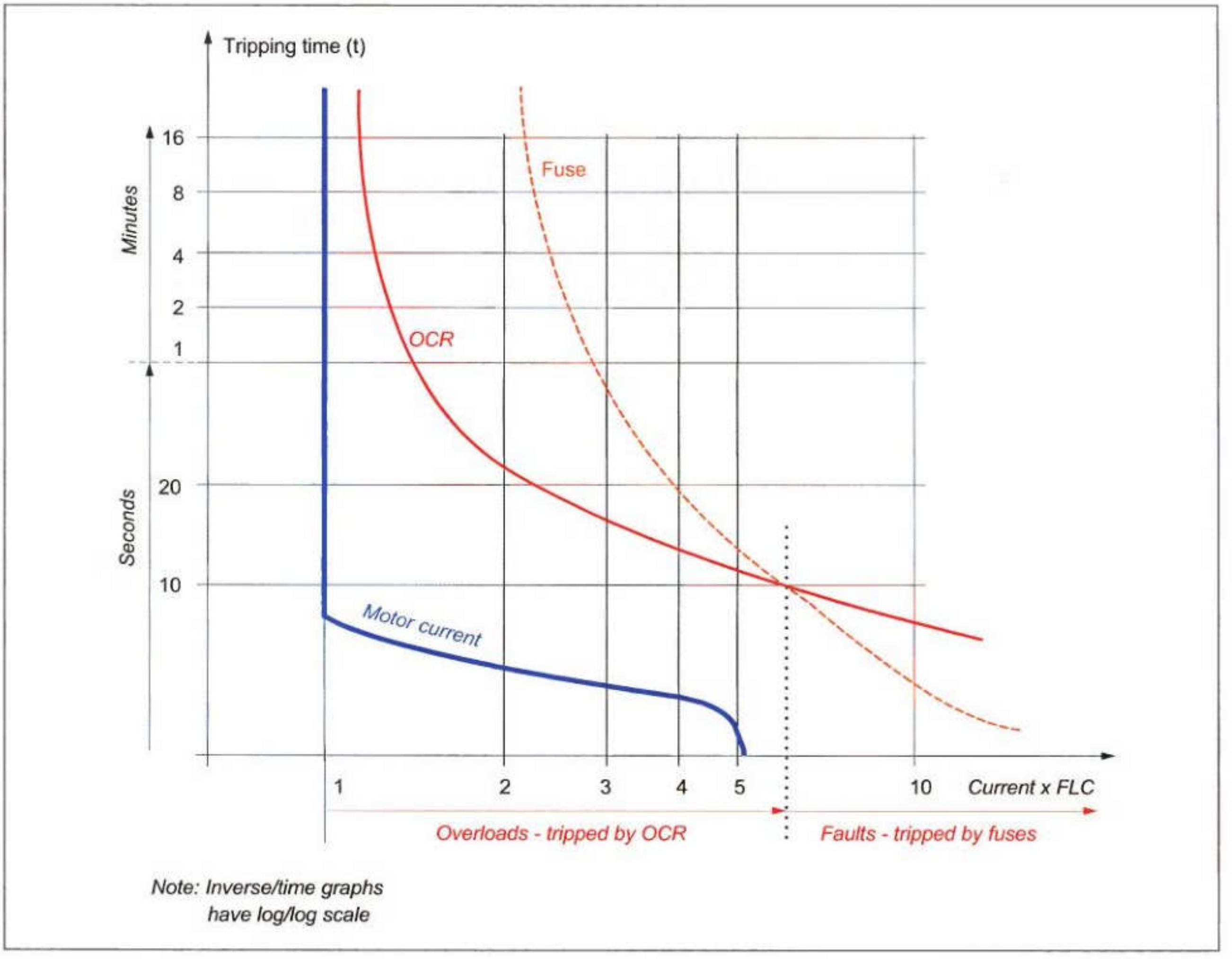


Figure 4.20 - Motor protection curves

QUESTION

A motor is protected by a thermal OCR and backup fuses. Can the motor exceed its rated temperature without being tripped by the protection?

ANSWER

Yes!
Although overheating is usually indicated by the current drawn by the motor rising above its rated value, a number of other situations can contribute to motor overheating:

- Very high ambient temperature
- inadequate ventilation
- a star-delta starter stuck in the star connection
- stopping and starting too often
- worn or dry shaft bearings.

The motor windings can only be protected against these conditions by using direct thermal protection.

There are three types of overcurrent relay (OCR) used for motor protection:

- Electronic
- thermal
- electromagnetic.

OCIT relays have largely superseded electromagnetic types as they have no moving parts (except for their output trip relay) and their very reliable tripping characteristics can be closely matched to the motor circuit. This type of relay is robust, smaller and lighter than the equivalent electromagnetic type.

A block diagram of such an electronic OCR is shown in Figure 4.21.

The block diagram of the electronic OCIT relay shows that the current and time settings can be adjusted over a limited range to match the motor FLC and run-up time. A self-test of the OCR performance can usually be applied with a fixed setting of, typically, six times FLC. The tripping-time can be measured and compared against the manufacturer's current/time characteristics.

Although electromagnetic devices with time delays can provide adequate protection against large, sustained overloads to motors that are operated well below their maximum output and temperature, they have been found to be inadequate for continuous maximum rated (CMR) motors.

Most LV motors are protected by less expensive thermal OCRs. Inverse time thermal OCRs usually work with bimetal strips, as shown in Figure 4.22. The strips are heated by the motor current and bend depending on the temperature. If the motor takes an overload current, the strips operate and open the incorporated normally-closed (NC) contact 95-96 which, in turn, trips out the line contactor to stop the motor.

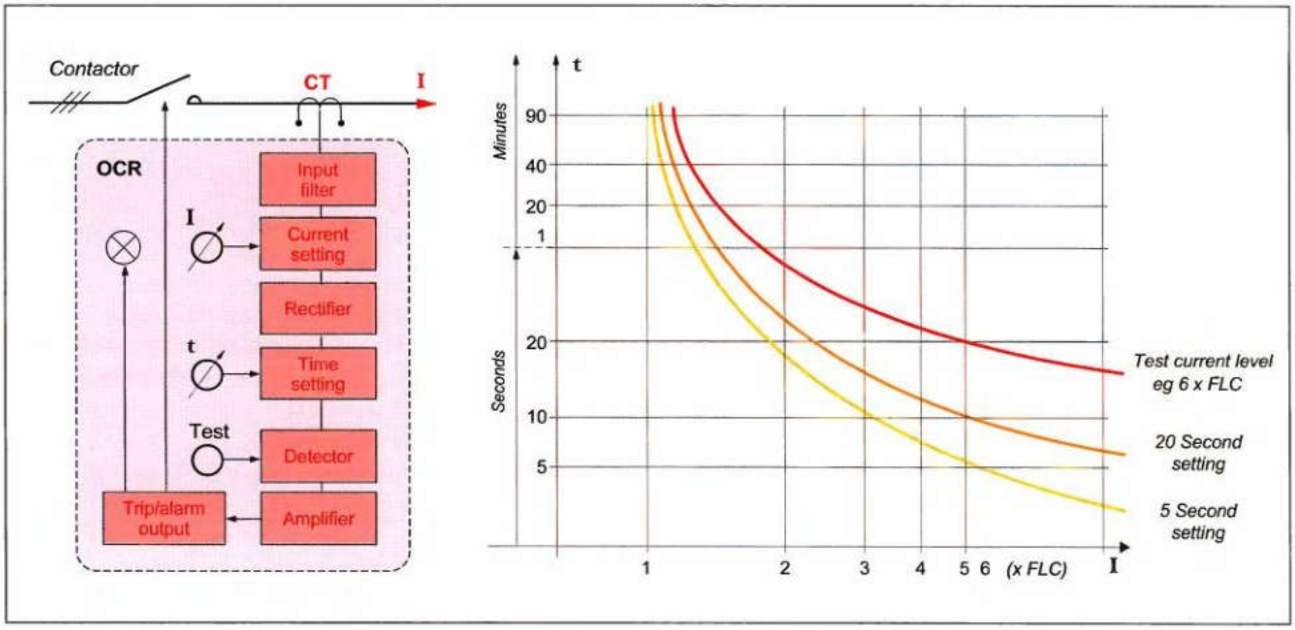


Figure 4.21 - Electronic overcurrent relay and I/t curves

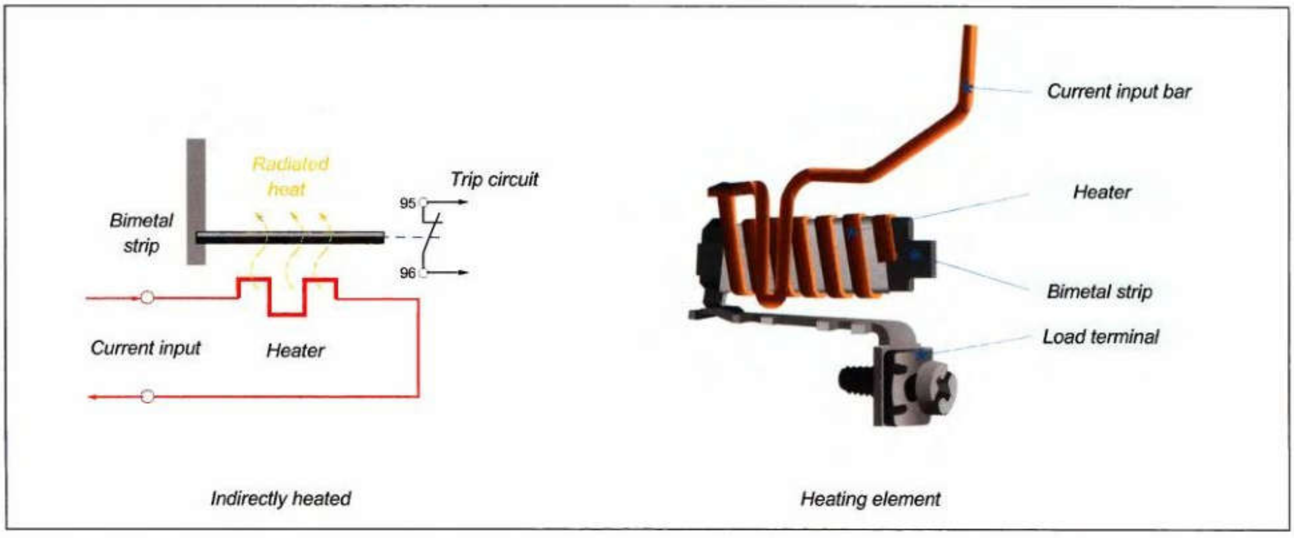


Figure 4.22 - Thermal overload relay action (single-phase is shown)

The minimum tripping current of such a device can be adjusted over a small range. This adjustment alters the distance the strips have to bend before operating the trip contact.

For larger motors, the heaters do not carry the full motor current. They are supplied from current transformers (CTs) that proportionally step-down the motor current so that smaller heater components may be used.

To operate correctly, induction motors must be connected to a three-phase AC supply. Once started, they may continue to run even if one of the three supply lines becomes disconnected. This is called single phasing and can result in motor burnout.

Single phasing, as shown in Figure 4.23, is usually caused when one phase out of the three-phase power supply system is missing for any reason (for example, a blown fuse, the contactor's main contact fails to close or a bad contact, etc). The effect of single phasing is to increase the current in the two remaining lines and cause the motor to become very noisy due to the uneven torque produced in the rotor.

An increase in line current due to single phasing will be detected by the protective OCR. The three thermal elements of an OCR are arranged in such a way that unequal heating of the bimetal strips causes a differential movement that operates the OCR switch contacts to trip out the motor contactor.

For large HV machines, a separate device, called a negative phase sequence (NPS) relay, is used to measure the amount of unbalance in the motor currents.

For star connected motor windings, the phase and line currents are equal so the line connected OCR is correctly sensing the winding current. If the overcurrent setting is exceeded during a single-phase fault, the motor will be tripped off.

The situation is not so simple with a delta connected motor. Normally, the line current divides phasorally between two phases of the motor windings.

The phase current is just over half the line current as

$$I_{PH} = \frac{I_L}{\sqrt{3}} = 0.577\, I_L$$

When one of the lines becomes open circuited, a balanced three-phase condition no longer exists. Now the sets of line and phase currents are no longer balanced.

The table below shows typical values of line and phase currents at various levels of motor loading during a single-phasing fault, as shown in Figure 4.23.

Healthy Condition (balanced)	**Single-phasing Fault Condition (unbalanced)**		
% of rated FLC	*% of rated FLC*		
	I_{L2} and I_{L3}	I_W and I_U	I_V
60	102	62	131
70	130	79	161
100	243	129	185

Table 4.2 - Typical line and phase current values

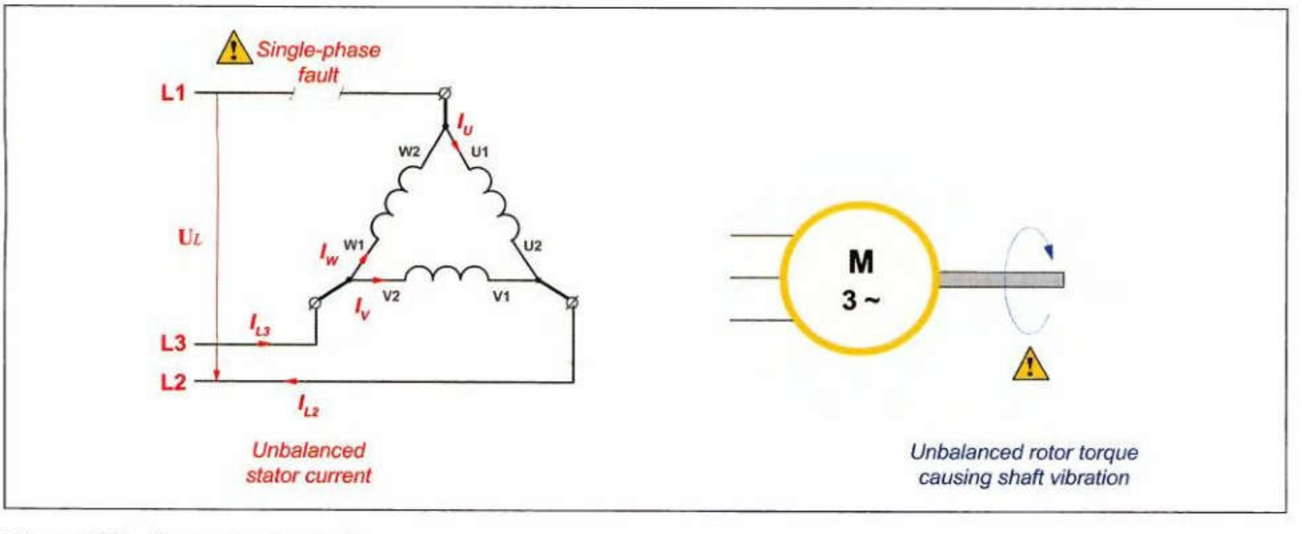


Figure 4.23 - Single-phasing fault

Note that the current in winding V1-V2 is considerably higher than that in the other two windings.

Look at the condition where the motor is at 60% of full load when single phasing occurs, the line currents are 102% of the full-load value, but the current in winding V1-V2 is 131% of its full-load value. The 102% line current will probably not activate a line connected OCR and the motor remains connected. However, the local overheating in winding V1-V2 of the motor will quickly result in damage.

Motors can be protected against this condition by using a differential type relay that trips out with unbalanced currents. In fact, most modern thermal OCRs for motors have this protection against single phasing incorporated as a normal feature. A differential action is shown in Figure 4.24.

If single phasing occurs when in operation on light load, the motor keeps on running unless the protection trips the contactor. If the motor is stopped, it will not restart. When the contactor is closed, the motor will take a large starting current but develop no rotating torque. The OCR is set to allow the starting current to flow long enough for the motor, under normal conditions, to run up to speed. With no ventilation on the stationary motor, this time delay will result in rapid and severe overheating.

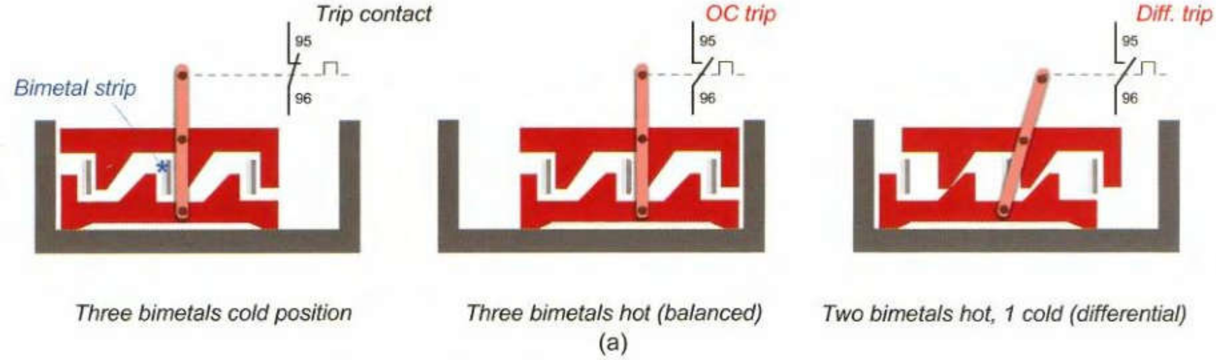
Worse still, if the operator makes several attempts to restart the motor, it will burn out.

If a motor fails to start after two attempts, you must investigate the cause.

Undervoltage protection is necessary in a distribution system that supplies motors. If there is a total voltage loss or blackout, all the motors must be disconnected from the supply. This is to prevent all the motors restarting together, which would result in a huge current surge, tripping out the generator again. Motors must be restarted in a controlled sequence after a supply failure.

Undervoltage (UV) protection for LV motors is provided by the spring-loaded motor contactor because it will drop out when the supply voltage is lost. For large HV motors, the UV protection function will be covered by an undervoltage release incorporated into an air circuit breaker (or motor starter protector) separate from the OCR function or it may be part of a special motor protection electronic relay which incorporates all of the necessary protection functions.

When the supply voltage becomes available, the motor will not restart until its contactor coil is energised. This will usually require the operator to press the stop/reset button before initiating the start sequence.



(a)

(b)

Figure 4.24 - (a) Single phasing protection (differential action) and (b) OCR internal components (top cover removed)

For essential loads, the restart may be performed automatically by a sequence restart system. This system ensures that essential services are restarted automatically on restoration of supply following a blackout. Timer relays in the starters of essential motor circuits are set to initiate startup in a controlled sequence.

4.9 Single-Phase Motors

Low power motors for power tools, domestic equipment, refrigerators, vacuum cleaners, etc are typically supplied at 220 V AC 50/60 Hz.

Common types are:

- Split-phase induction motor
- capacitor start/run induction motor
- shaded-pole induction motor
- AC commutator motor.

Split-phase induction motor

A single-phase induction motor has a cage rotor similar to that used in a three-phase type. A single stator winding produces a pulsating magnetic field when energised with single-phase AC current. This field cannot exert a rotating force on the cage rotor.

One method used to produce a rotational force is to employ two stator windings fitted at 90° to each other with both connected across the same supply. This is the split-phase motor. To get the effect of a shifting magnetic field (and therefore induce a rotating force into the rotor), one winding is electrically phase shifted by adding capacitance in series with one of the windings.

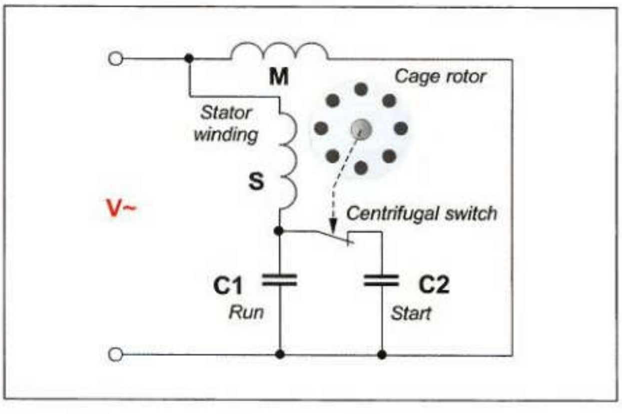


Figure 4.25 - Capacitor-start motor circuit

Capacitor start/run induction motor

When the motor has started to run, the additional phase winding circuit may be disconnected and the rotor will continue to be pulsed around by the magnetic flux. This is called a capacitor start motor, which is only useful for driving a very light load.

For starting and running, two capacitors are used in circuit, as shown in Figure 4.25.

During the starting period, the two paralleled capacitors create a large-phase angle to the 'S' winding current. As the rotor runs up to speed, a switch cuts out one of the capacitors. The switch may be a centrifugal type on the rotor shaft or a current-operated, time-delay relay in the motor terminal box. This type of motor gives good starting and running torque with a reasonable power factor. Most split-phase motors are arranged for a 4-pole stator winding so, at 50 Hz, its synchronous (flux) speed will be 25 rev/s or 1500 rpm. As with all induction motors, the rotor will slip causing the shaft speed to be about 24 rev/s or 1440 rpm on no load. On load, a single-phase induction motor will run with greater slip and operate with less efficiency than a three-phase version.

Shaded-pole induction motor

This is a low torque machine useful for low power drives, such as small cooling fans in electronic equipment.

Figure 4.26 shows how the face of each stator pole is partially split, with one side carrying a thick copper wire called a shading ring. The pulsating AC flux divides into each half of the pole, but is time delayed in the part with the shading ring. This is due to an induced current in the ring that opposes flux change in the shaded part. To the rotor, this

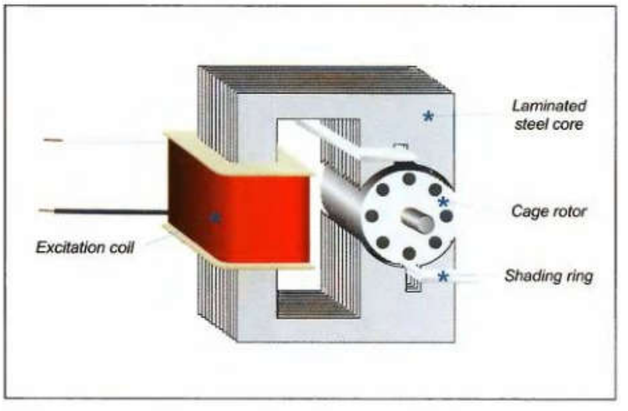


Figure 4.26 - Shaded-pole motor construction

delay appears as a flux shift across the overall pole face, which drags the rotor with it by the normal induction motor action. The developed torque is small and the machine is not very efficient, but it is an inexpensive drive for very low power applications. As with all induction motors, the shaft base speed is fixed by the supply frequency, so at 50 Hz the maximum speed is 3000 rpm and shaft loading will cause the rotor to slip below this value.

AC commutator motor

This is a DC series motor, which is designed to operate very effectively on an AC voltage supply (see Figure 4.27).

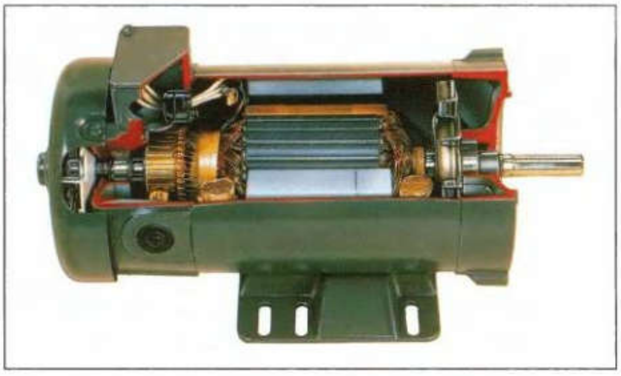


Figure 4.27 - Commutator motor construction

The shaft torque produced is given by $T = \Phi \times I$, where Φ is the flux produced by the series connected stator winding and I is the armature (and supply) current in the rotor. As Φ is produced by the same current, the torque is essentially $T = I^2$, which makes this single-phase AC motor more powerful than induction types.

At 220 V AC, the shaft speed on light load is typically 12-18,000 rpm and is easily controlled by an additional series resistance or an electronic voltage regulator. The speed falls rapidly with increased load torque.

This type of motor is used in equipment rated up to a few hundred watts, such as power drills, sanders, jigsaws, etc.

The commutator and brush contacts will cause some sparking in normal operation, which can cause radio/television interference, so a high frequency voltage suppressor is usually fitted to this type of motor.

4.10 Maintenance

The maintenance requirements for cage-rotor induction motors are very simple:

- Keep insulation resistance high and contact resistance low
- lubricate bearings correctly
- ensure both the interior and exterior are always clean and dry.

Provided these requirements are met, an induction motor should give trouble-free service during its long life.

QUESTION

What is the most common cause of induction motor failure?

ANSWER

Failure of stator insulation due to dampness is a major problem with marine motors.

Open ventilated motors are most at risk, particularly when they are not used for long periods.

For motors installed on the outer decks (eg bow thrusters, cargo cranes, mooring winches and ventilation fans including hold ventilation), anti-condensation heaters should be regularly checked to see that they are actually working and keeping the motor dry. These are normally space heaters, usually 200 V AC, which are switched off automatically when the motor starts.

For all motors, cleanliness is extremely important. A regular cleaning routine is required to remove harmful deposits of dust, dirt, grease and oil from both inside and outside the motor. The cleaning of the external surface is particularly important for totally enclosed motors that run continuously. The heat generated in these motors is removed through the external surface. A thick layer of dust will reduce the heat dissipation and create very high temperatures. Internal dust and dirt in open ventilated motors must be regularly removed by blowing or extraction and ventilation screens and ducts cleared out.

If motors are to be blown out, the air used must be absolutely dry and the pressure should not be more than 1.75 bar. If the pressure is higher than this, it forces the dust into the winding insulation rather than removing it.

When blowing out a motor, remember to cover up other machines in the area to protect them from flying dust. Suction cleaning is better than blowing out.

QUESTION

How often should a motor be cleaned?

ANSWER

This will generally be determined by the local conditions and the type of ventilation. Only the external surfaces of totally enclosed motors will require *regular* cleaning. However, both the outside and inside of open ventilated motors will require routine attention. The inside of a totally enclosed motor can be cleaned if the motor has been dismantled for bearing replacement. Motors in areas where considerable amounts of airborne dust are expected (hatch ventilation fans are a good example) will require more frequent cleaning.

Contamination by oil and grease from motor bearings is often a cause of insulation failure. The insulation should be cleaned by brushing or spraying with slow-drying electro solvent. Badly contaminated motors may require total immersion of the stator windings in cleaning fluid. Broken or missing bearing covers must be repaired or replaced to prevent grease escaping.

When a motor has been dismantled for cleaning and overhaul, it should be thoroughly inspected. In this way, faults can be detected before they evolve into a major breakdown.

Stator

Look at the stator windings for damaged insulation caused by careless replacement of the rotor into the stator. Discoloured insulation is an indication that the winding has been overheated. The cause of overheating must be found and corrected before allowing the motor back into service.

Carefully examine the stator core for signs of rubbing with the rotor, usually caused by a worn bearing. Even slight rubbing of the rotor against the stator will generate enough heat to destroy the stator insulation. Replace the bearings if necessary.

Laminated steel core plates that have been badly scored may cause a local hot spot to be generated when the motor is running. This is because the iron losses will increase in the damaged area. After the motor has been put back into service with new bearings, check the motor running temperature. After a short period of service, dismantle the motor and check for discolouration at the core damage, which will indicate local heating. If you suspect core hot spots then the motor core will need to be

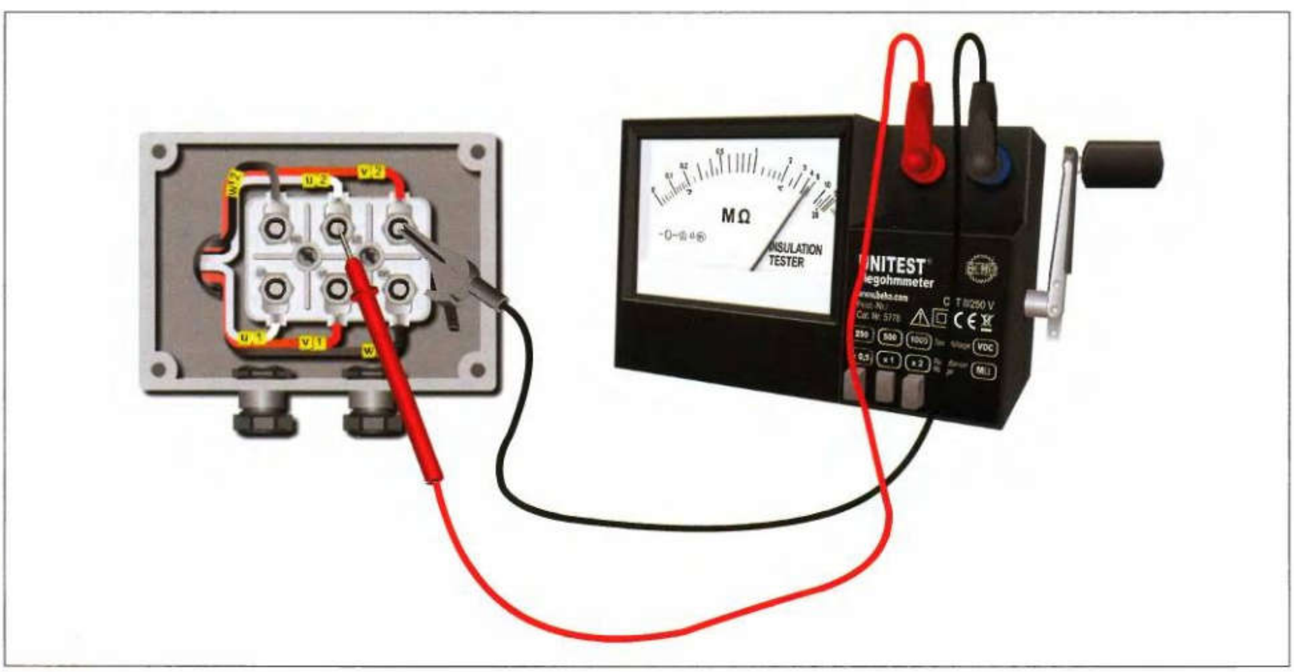


Figure 4.28 - Motor IR test

dismantled for the laminations to be cleaned and re-insulated (which is a shore job).

The insulation resistance reading is the best indication of moisture in the motor windings. Breakdowns due to insulation failure usually result in an earth fault, short-circuited turns in a phase, or phase to phase faults.

QUESTION

How do you check the insulation resistance between phases on an induction motor?

ANSWER

Larger motors are usually six terminal, which means that all six ends of the stator windings are brought out to the terminal block. Links between the terminals are used to star or delta connect the motor. Disconnect the supply leads and remove the links. Test between phases with an insulation resistance tester, as shown in Figure 4.28.

A problem can arise on small, three terminal motors where the star or delta connection is made inside the motor. Only one end of each winding is available at the terminal block. Phase to phase insulation resistance cannot be checked. If a three terminal motor is to be rewound, consider asking the repairer to convert it to a six terminal arrangement.

Bearings

Induction motors are fitted with ball and/or roller bearings. These bearings are robust and reliable and should give very little trouble provided they are properly fitted, kept absolutely clean and lubricated correctly.

Many engineers argue that if a bearing seems to be operating correctly it should not be tampered with.

Portable vibration detection results, sampled periodically and analysed, can be a very useful way to recognise the onset of a bearing failure. Bearing temperature, eg using embedded detectors or with portable infrared (IR) spot checks, is another indicator of the general health of a shaft bearing.

It is not easy to predict (with any degree of certainty) the unexpired life of bearings that have already run for some time. Also, inspection may not show damage to raceways and rolling elements in areas hidden from view. The best policy is to renew the bearings as part of a planned maintenance programme. If this is not possible because of cost or a shortage of replacements, then bearings should be removed, cleaned and inspected for signs of damage before a decision to refit or renew is taken.

Before opening up a bearing, make sure that the complete area around the housing is clean and dry. Manufacturers recommend that bearings should be removed from the shaft as seldom as possible, but cleaning and inspection is best done with the bearing off the shaft. If the correct size of wedges or pullers is used, removal should not cause any damage. Bearings should be cleaned by immersion in a solvent, such as clean white spirit or clean paraffin, then thoroughly dried in a jet of clean, dry compressed air. Bearings should not be spun by the air jet because skidding can damage the rolling elements and raceways.

Once dry, the bearing must be lightly oiled. Any traces of metal particles, such as brass, indicate cage wear and the bearing must be replaced. If there is no evidence of metal particles, carefully examine the raceways and rolling elements for signs of wear or damage. Hold the inner race in one hand and slowly turn the outer race. Any sticking or unevenness in the rotation requires a re-wash of the bearing and rotation in the cleaning fluid. If the sticking persists, the bearing must be rejected. Similarly, bearings with visible signs of corrosion, overheating or damage, and those with a noticeable degree of roughness in rotation, should also be replaced.

When fitting a bearing to a shaft, first clean the shaft and apply a thin film of light oil. Set the bearing square on the shaft and, with a tubular drift (pipe), force the bearing against the shaft shoulder. The drift should bear on the inner race as close to the shaft as possible. Large bearings can be heated for 10-15 minutes in clean mineral oil up to 80°C to facilitate fitting. Lubricate the bearings with the correct type and quantity of grease as recommended by the manufacturer. Fill the bearing about one third to one half full with grease. Overgreasing causes churning and friction, which results in heating, oxidation of the grease and possible leakage through the seals.

On account of the high ambient temperature and excessive vibration that many marine motors endure, grease life can be short and fresh grease should be applied at regular intervals. Unless the bearing housing has a vent hole to allow excess grease to escape, it will be necessary to clean out the bearing housing before charging it with fresh grease. Because of the vibration on ships, bearings can be damaged when the motor is not running.

The shafts of stationary motors should be periodically rotated a quarter turn to minimise vibration damage to the bearings.

Rotor

Maintenance of cage rotor induction motors tends to mainly involve the stator windings and bearings. Cage rotors require little or no special care in normal service. Inspect for signs of damage and overheating in the cage winding and its laminated steel core. Make sure that all core ventilating ducts are clean and clear. If an internal fan is fitted it must be in good condition if it is to provide adequate cooling.

QUESTION

A cage-rotor induction motor has been flooded with seawater and its insulation resistance is down to zero MΩ. What is the procedure for putting the motor back into service?

ANSWER

The main problem is to restore the insulation resistance of the stator winding to a high value. This is achieved in three stages:

- Cleaning
- drying
- re-varnishing.

Salt contamination can be removed by washing with fresh hot water. Any grease or oil on the windings has to be removed using a degreasant liquid.

Dry the stator windings with low power electric heaters or lamps with plenty of ventilation to allow the dampness to escape.

Alternatively, the windings can be heated by current injection from a welding set or from a special injection transformer. Be sure to keep the injected current level well below the motor's full load rating.

With the windings clean and dry, and if the IR test remains high over a few hours, apply a couple of coats of good quality air-drying insulating varnish.

The motor starter and other control equipment should be regularly inspected to check and maintain the following items:

Enclosure

Check for accumulations of dirt and rust. Any corroded parts must be cleaned and repainted. Examine the starter fixing bolts and its earth bonding connection, particularly where high vibration is present, eg in the steering flat and the forecastle.

Contactors and relays

Check for any signs of overheating and loose connections. Remove any dust and grease from insulating components to prevent voltage breakdown by surface tracking. Ensure that the magnet armature of contactors moves freely. Remove any dirt or rust from magnet faces that may prevent correct closing.

Contacts

Examine for excessive pitting and roughness due to burning. Copper contacts may be smoothed using a fine file. Copper oxide, which acts as a high resistance, can be removed using glasspaper.

Do not file silver alloy contacts or remove silver oxide as it acts as a good conductor. A thin smear of electrical contact lubrication helps to prolong the life of all contacts. When contacts have to be replaced, always replace both fixed and moving contacts in pairs. The entire set of contacts in three-phases should be replaced.

Check contact spring pressure and compare adjacent contact sets for equal pressure. Examine power and control fuse contacts for signs of overheating and lubricate the contact blades on fuse holders.

Connections

Examine all power and control connections for tightness and signs of overheating. Check flexible leads for fraying and brittleness.

Overcurrent relays

Check for proper settings. A thorough OCR performance test may be carried out by using the incorporated test buttons.

Control operation

Observe the sequence of operation during a normal start up, control and shutdown of the motor. Remember to check that the emergency stop buttons are operational.

Chapter Five
Ancillary Electrical Services

5.1 Navigation and Signal Lights

The number, position and visible range of navigation lights on board ships is prescribed by the International Maritime Organization (IMO) in the 'International Regulations for Preventing Collisions at Sea' (COLREGs). In the UK, the National Authority for maintaining marine safety standards is the MCA (Maritime and Coastguard Agency).

The most common arrangement is to have five specially-designed navigation running lights referred to as foremast, mainmast (or aftmast), port, starboard and stern (see Figure 5.1).

Two anchor lights, fitted forward and aft, may also be switched from the navigation light panel on the bridge. The side lights are red for port and green for starboard, while the other lights are white. For vessels of more than 50 metres in length, the masthead light(s) must be visible from a range of 6 nautical miles and the other navigation lights from 3 nautical miles. To achieve such visibility, special incandescent filament lamps are used, each with a typical power rating of 65 W, but 60 W and 40 W ratings are also permitted in some cases.

Due to the essential safety requirement for navigation lights, it is common practice to have two fittings at each position, or two lamps and lampholders within a dual fitting.

Each light is separately supplied, switched, fused and monitored from a navigation light panel in the wheelhouse. The electric power is usually provided at 220 V AC, with a main supply fed from the essential services section of the main switchboard.

An alternative or standby power supply is fed from the emergency switchboard. A changeover switch on the navigation light panel selects the main or standby power supply.

The navigation light panel has indicator LEDs and an audible alarm to warn of any lamp or lamp circuit failure. Each lamp circuit is monitored by the electronic circuit for the lamp current. A basic navigation light control panel is shown in Figure 5.2.

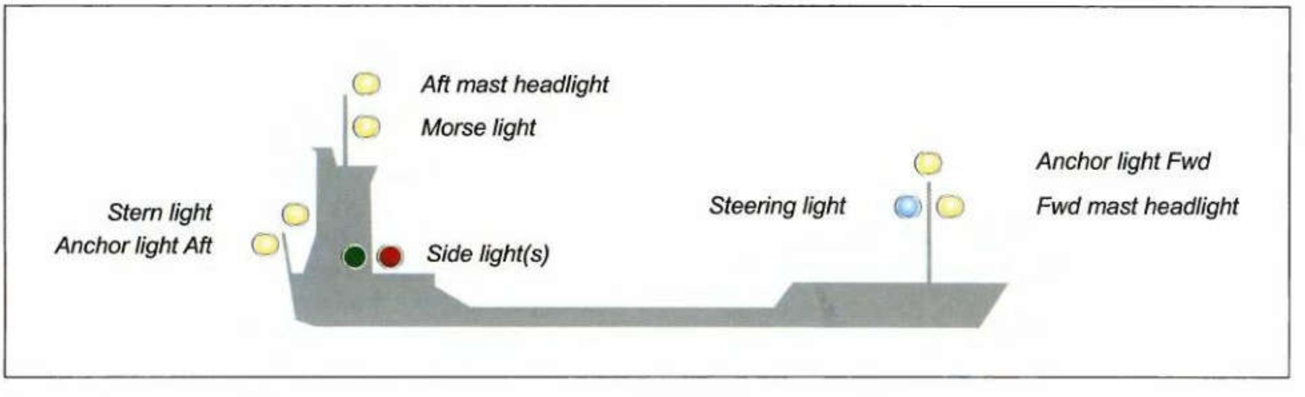


Figure 5.1 - Ship navigation lights arrangement

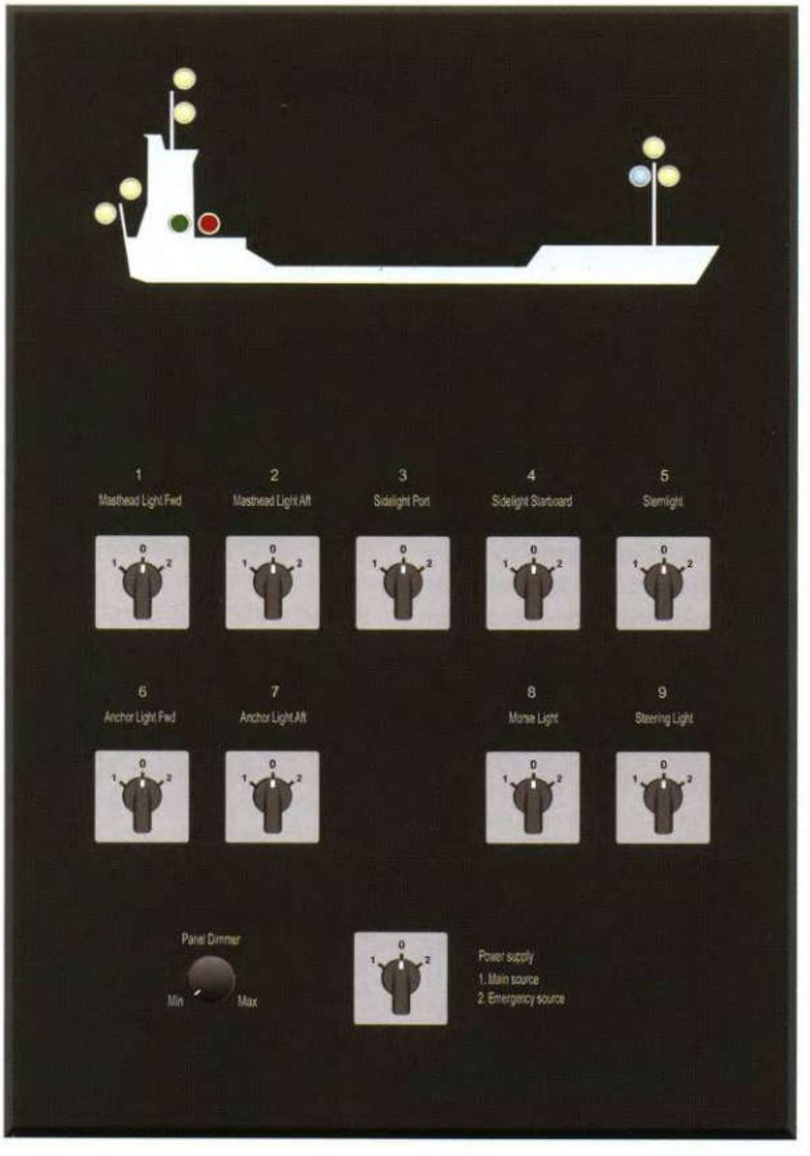


Figure 5.2 - Navigation light panel

Various signal lights with red, green and white colours are arranged on the signal mast, as shown in Figure 5.3. These lights are switched in combinations that signal states relating to various international and national regulations.

Pilotage requirements, health, dangerous cargo conditions, etc are all signalled with these lights. White morse code flashing lights may also be fitted on the signal mast.

The NUC (Not Under Command) state is signalled using two all-round red lights vertically mounted at least 2 m apart. These important lights are fed from the 24 V DC emergency supply, but some ships may also have an additional NUC light-pair fed from the 220 V AC emergency power supply.

5.2 Emergency Lighting

Depending on the ship's Classification and tonnage, the Safety of Life at Sea (SOLAS) Convention prescribes requirements for emergency lighting throughout the vessel. Emergency lighting fixtures must be marked as such for easy identification (eg with a red disk).

Most of the emergency lighting is continually powered from the ship's emergency switchboard at 220 V AC. Emergency lights at the staircases and through the escape route may be supplied from the ship's 24 V DC battery supply.

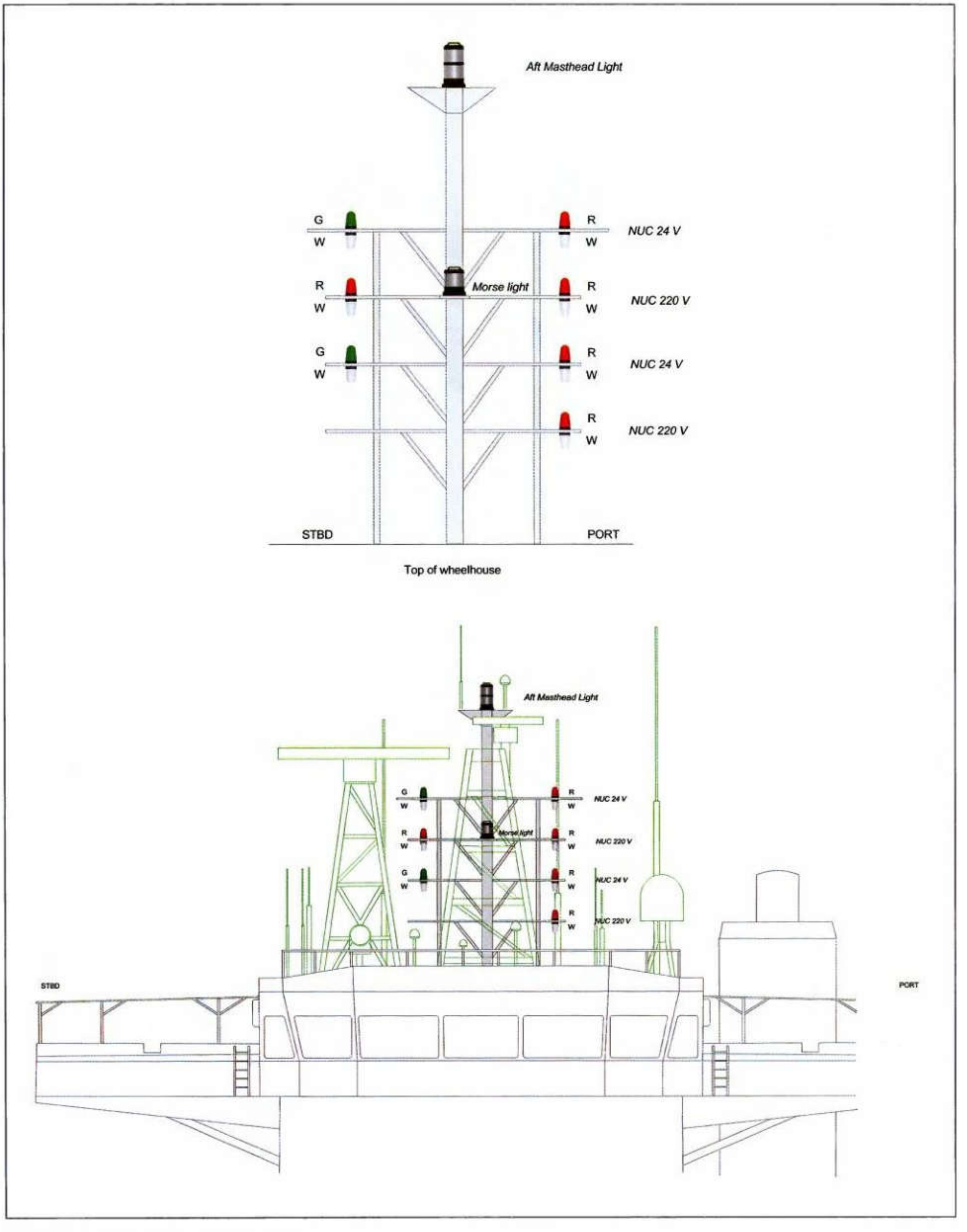


Figure 5.3 - Signal lights arrangement

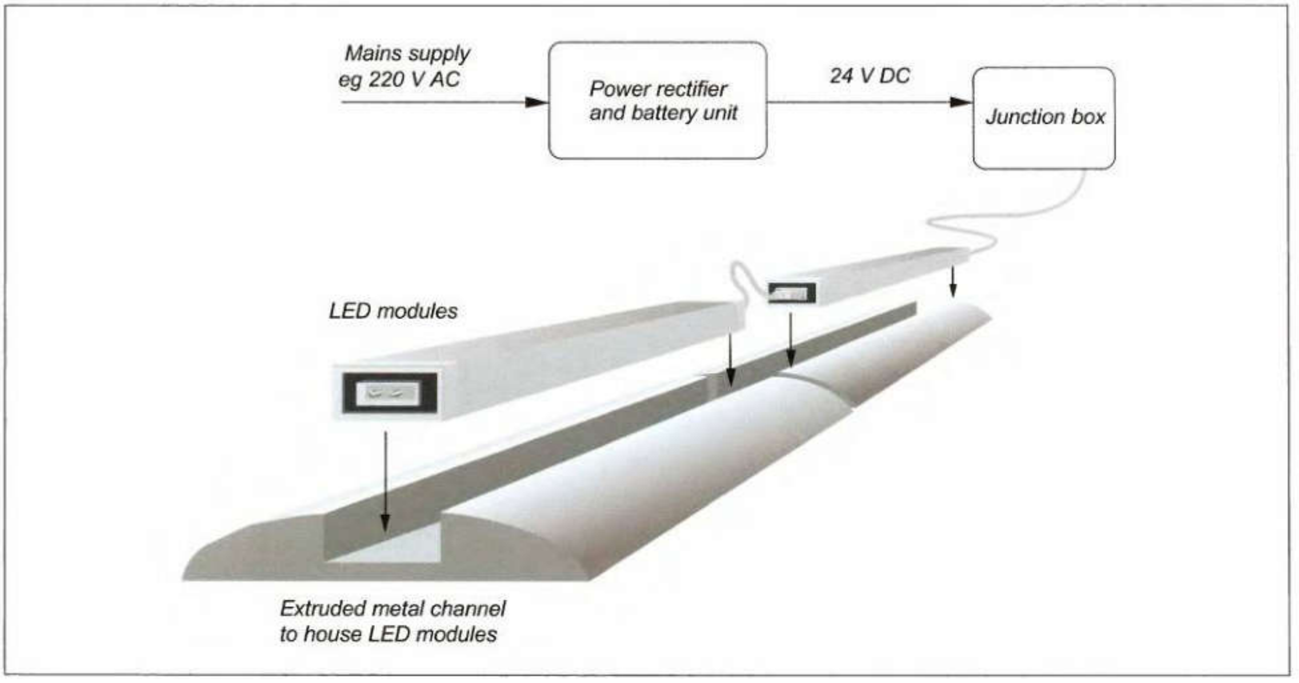


Figure 5.4 - Low location lighting (LLL)

The main and emergency lighting systems (sources of electrical power, associated transformers, switchboards and central lighting distribution panels) must be arranged so that a fire or other incident would not cause the failure of both systems, ie the components of the main and emergency lighting systems must not be located in the same rooms.

If the main power supply fails, the emergency lighting system must switch on automatically. Local switches may be provided only where the ability to switch off the emergency lighting is required, eg in the wheelhouse.

Where, in accordance with SOLAS, a ship is divided into main fire zones, at least two circuits are to be provided for the lighting of each main fire zone, and each of these must have its own power supply circuit. One circuit can be supplied from the emergency switchboard, if this is permanently in service. The supply circuits must be routed so that a fire in one main fire zone does not interfere with the lighting of the other zones.

Lighting fixtures in cargo holds must be installed so that, when properly used, there is no overheating of the lighting fixtures or their surroundings, even when the ship is loaded.

Adequate illumination is to be provided for the outboard transfer arrangements, the deck region where persons come on board or leave and at the control positions for the mechanical pilot hoist.

Passenger ships and RoRo passenger ships must also be fitted with a special battery-supported emergency lighting system along main escape routes in the engine room and accommodation and at the lifeboat positions on deck. Generally, the emergency lights in the accommodation illuminate immediately on mains failure. The system's maintenance-free battery, usually Ni-Cd (nickel-cadmium), is continually trickle-charged from the normal mains supply via a transformer/rectifier circuit. This battery is then available to supply the lamp via a DC to AC inverter when the mains power is absent.

This power supply arrangement is called an uninterruptible power supply, or UPS, and it will only function for a few hours. The battery-supported light fittings can be simply tested by switching off the normal mains power supply or, in some cases, by a test switch on the actual fitting.

Passenger ships carrying more than 36 passengers are required, by the IMO, to be fitted with low location lighting (LLL) to identify escape routes where normal emergency lighting is less effective due to the presence of smoke. An LLL system must function for at least 60 minutes after activation and it should indicate a line along the corridors of an escape route.

Figure 5.4 shows the main components of an LLL system, where the LEDs are wired onto a printed circuit board within a clear polycarbonate rectangular tube that has connectors at each end.

A similar arrangement is available using low power incandescent lamps.

Periodic inspection and testing of all emergency lights is an essential requirement on all ships.

5.3 Refrigeration and Air Conditioning

Refrigeration

Whatever the size or role of the ship's refrigerators, the basic principle is common to them all. Each will have an evaporator (cooling unit), a refrigerant compressor and a condenser.

The refrigerant used is generally Freon-R417 (reefer container units use R-134a, R404 or other types of refrigerant), which is classified as almost harmless to the ozone layer if it escapes into the atmosphere.

Freon refrigerants in general use are colourless almost odourless, non-toxic, non-corrosive and non-flammable. However, when exposed to an open flame they produce toxic gases that are severe respiratory irritants capable of causing death.

Additional components to the basic refrigerant cycle may include filter driers, heat exchangers, accumulators and pre-coolers. Also required are the operating and protective controls, such as thermostats, relays, defrost controls and overcurrent trips.

For units bigger than a domestic-sized refrigerator, the compressor motor will invariably be a three-phase type driving a reciprocating compressor. The domestic version will usually be a single-phase motor driving a rotary compressor.

The basic refrigerant circuit of a direct (or primary) expansion system used for the cooling of meat and vegetable rooms is outlined in Figure 5.5.

Each cold room is fitted with a thermostat that operates a solenoid valve between set temperature limits. The quantity of refrigerant flowing in the system is regulated by the expansion valve. This valve is controlled by a liquid phial that is connected by a capillary tube attached to the vapour return pipe at the outlet of the evaporator.

When the room temperature falls to the preset level, the thermostat de-energises the solenoid valve to stop circulation of the refrigerant. The resulting pressure drop in the compressor suction line will operate a low pressure cutout valve and stop the compressor.

The rooms or compartments are cooled by natural air circulation through the evaporator coils or by forced air from a fan blowing across a bank of cooling tubes.

In a domestic refrigerator, the cooling effort is controlled by using a control thermostat to switch the compressor on or off.

The hermetically sealed compressor motor is the split-phase type, with two separate windings, start and run, as shown in Figure 5.6.

The motor is accelerated by connecting both start and run phase windings to the supply. When the motor reaches about 80% of its rated speed, the start winding is tripped out of circuit. For compressor drives, this switch is usually in the form of a current-operated relay that is fitted adjacent to the compressor.

QUESTION

If the motor terminal markings are unknown, how could you identify the start, run and common terminal connections?

ANSWER

The start winding (being short-time rated) has a higher resistance than the run winding, so a resistance check should identify the terminals:

Using a multimeter on the low resistance range, find the two terminals that have the highest resistance between them. These are the start and run terminals. The remaining terminal must be the 'common'.

Connect one lead of the meter onto the common terminal and touch the other meter lead onto the other terminals in turn and note the readings.

The highest reading indicates the start winding terminal. The other remaining terminal is the run connection. Typically, the run winding is 1.5-6 Ω and the start winding is 6-22 Ω.

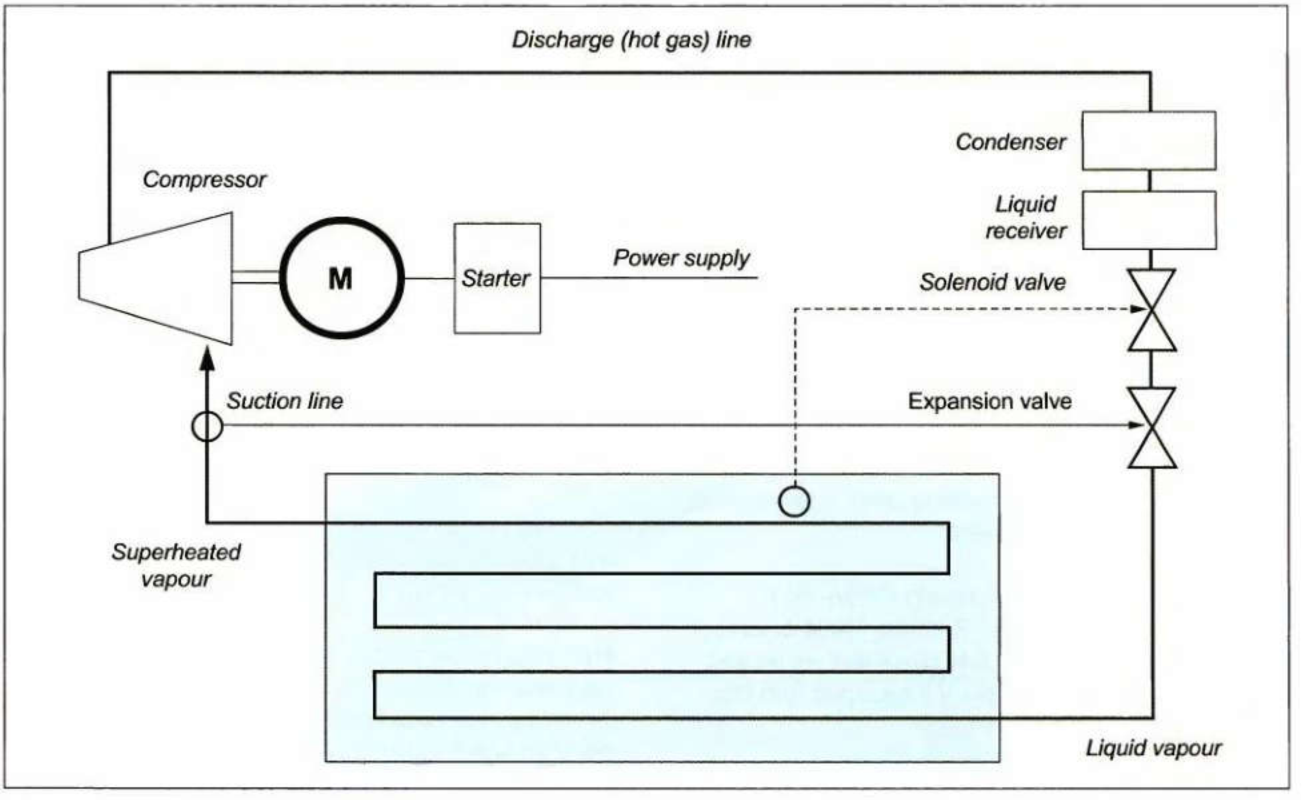


Figure 5.5 - Refrigeration circuit

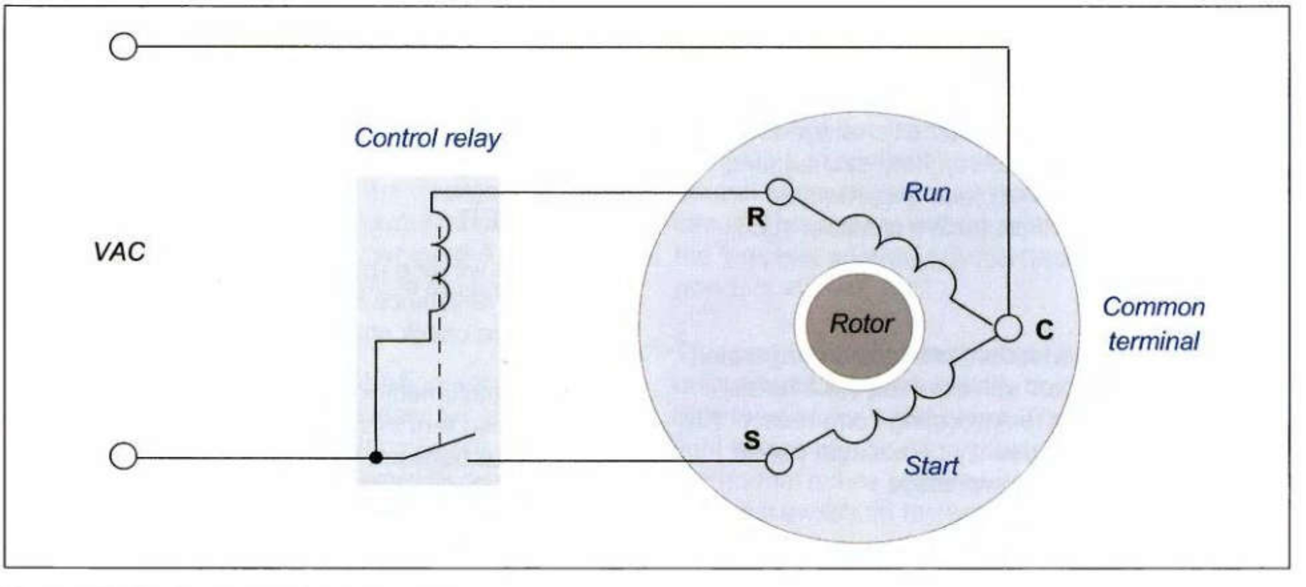


Figure 5.6 - Basic compressor motor control

The main temperature control device in the refrigerator is the thermostat which senses the evaporator temperature via a capillary tube. The set temperature is adjusted by a control knob that tensions the control spring against the pressure of the bellows.

For motor protection, a bimetallic OCR trip is included as part of the control relay alongside the compressor. The motor supply current either passes directly through a bimetal strip or disc or the bimetal is heated indirectly from a small resistance heater alongside it. A motor overcurrent will cause the bimetal to deflect and cause a snap action switch to open.

Figure 5.7 shows the complete circuit of a simple domestic refrigerator (ie without timers, automatic defrost or air circulation fans).

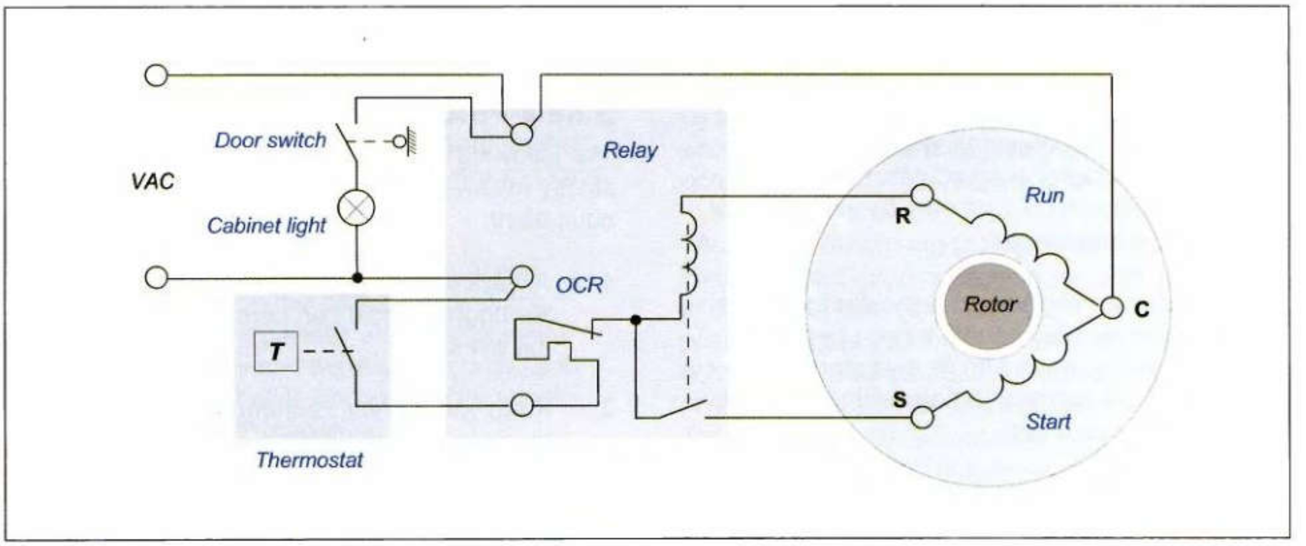


Figure 5.7 - Domestic refrigerator electric circuit

When the evaporator temperature rises, the thermostat switch closes, allowing current to flow through the motor run winding and the relay solenoid coil. This current is initially high, causing the solenoid to close the relay switch to allow current into the start winding.

The motor will now begin to accelerate from standstill, causing its run winding current to reduce to a level where the start-relay will drop off. The motor will now run continuously on the run-phase only. When the evaporator reaches its set temperature, the thermostat resets and the motor is switched off.

The most common way to achieve automatic defrosting of the evaporator is to use a time switch to cut out the refrigeration circuit and initiate a defrost heater circuit. The timer is generally an electronic relay with a set of changeover contacts.

A bimetallic defrost thermostat controls the defrost heater in or below the evaporator. Most defrost thermostats close at 20°F ± 5° and open at 55° ± 5°. Defrost periods may vary from 15 to 45 minutes with up to four defrost cycles in 24 hours depending on the fridge/freezer design.

Some refrigerators and freezers may have electric heaters fitted for various duties such as a dewpoint heater (to prevent sweating on the cabinet in the freezer area) and a compartment divider panel or stile heater (to prevent sweating on the panel).

Additionally, there may be condenser and evaporator fans that are driven by single-phase, shaded-pole type motors.

Air Conditioning

Air conditioning is a process that heats, cools, cleans and circulates air and controls its moisture content. The air must be delivered with a definite temperature and specified relative humidity.

For summer duty, the usual method is to cool the incoming air to a temperature below the dewpoint to allow condensation to occur until the mixture has the desired specific humidity, then heating the air to the required delivery temperature and relative humidity. In winter, the incoming air may have to be heated and have water added to achieve the correct inlet conditions. In most plants, the bulk of the mixture is recirculating air, with fresh air intake forming about one third of the total required. The amount of make-up air is a statutory requirement, typically between 17 m^3/hr and 28 m^3/hr.

The electrical aspects of accommodation air conditioning (A/C) comprises the power equipment of motors and starters for the compressor(s), fans and seawater cooling pumps. Associated control equipment will include electric solenoid valves, high and low pressure and temperature switches, together with safety cutouts for overcurrent, loss of refrigerant, low compressor oil pressure, etc.

The usual air conditioning system used for the accommodation spaces of cargo ships is the central single duct type, shown in Figure 5.8. In its simplest form, a single compressor serves the whole accommodation.

The compressor is generally a multi-cylinder reciprocating type with a power rating in the range of 20-100 kW, although rotary vane or screw action compressors may also be encountered. Large passenger vessels may have a total power requirement of more than 5 MW for the AC compressor drives to maintain air delivery to the hotel and staff accommodation areas. Capacity control of the reciprocating compressor is by automatic unloading of cylinders by valve control using servo oil pressure.

The compressor, air fan and seawater pump are driven by simple fixed-speed, three-phase AC induction motors, each with its own starter and supplied from a distribution board fitted in the air conditioning plant room.

Routine electrical maintenance and fault finding on the motors and starters will involve cleaning, checking of connections, IR (megger)/continuity tests and running tests as described in Chapter 4.

Inspection of connections and correct operation of any electric heaters must also be performed. Heaters may be used for heating the compressor crankcase oil and for separating the refrigerant from the oil in an oil reservoir.

Regular inspection and testing of control and safety thermostats and pressurestats should be carried out in accordance with the manufacturer's instructions. In particular, the compressor's low oil pressure alarm and trip circuit should be tested periodically for correct operation.

Safety Precautions

The following safety precautions must be strictly followed when working with refrigeration equipment.

1. Always wear goggles or safety glasses. Refrigerant liquid can permanently damage the eyes.

2. Keep your hands, clothing and tools clear of the fans when the refrigeration unit is running. If it is necessary to run the unit with covers removed, be very careful with tools or meters being used in the area.

3. Use caution when working with a refrigerant or refrigeration system in any closed or confined area with a limited air supply. Refrigerant will displace air and can cause oxygen depletion, resulting in suffocation and possible death.

4. Be aware that refrigerants used in the systems, in the presence of an open flame or electrical arc, produce toxic gases that are severe respiratory irritants capable of causing death.

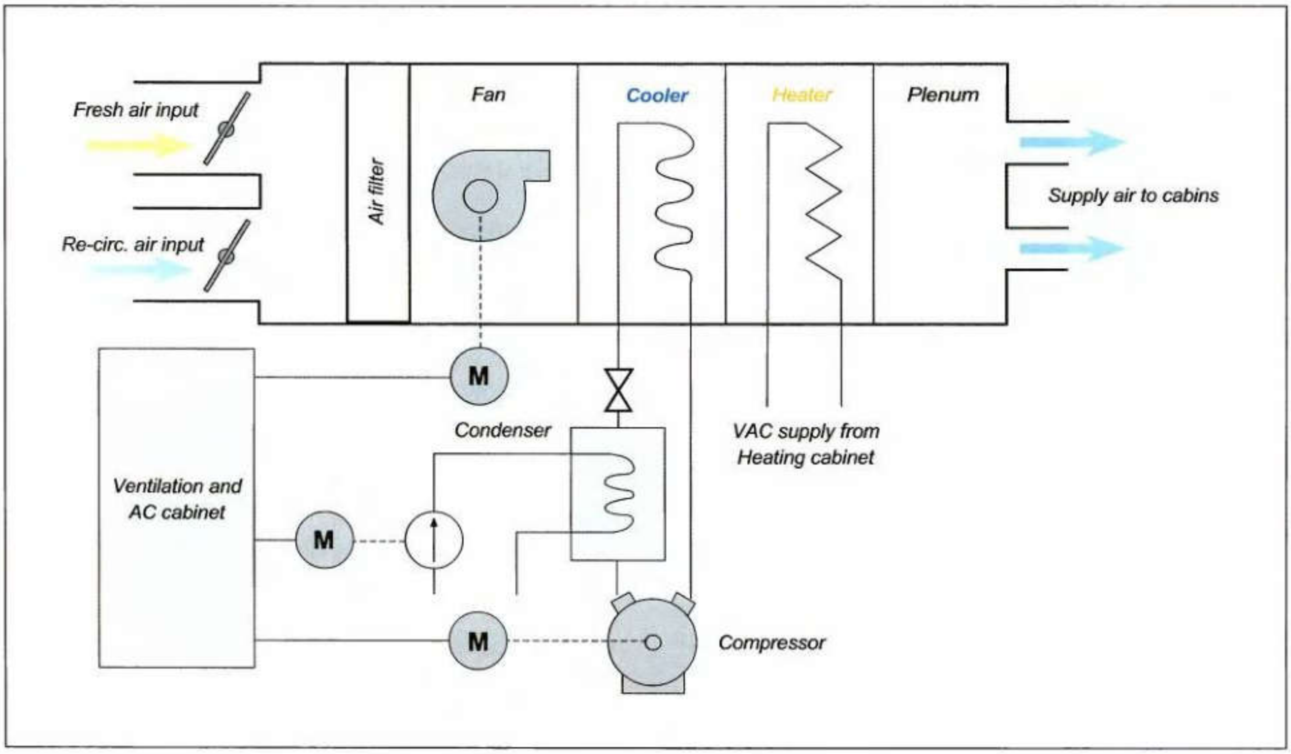


Figure 5.8 - Air-conditioning scheme and main components

5.4 Cathodic Protection

The outer surface of a ship's hull is subjected to electrochemical attack by corrosive currents that flow between areas of the hull, which are at slightly different electric potentials.

Dissimilar metals, variations in structural and chemical uniformity in hull plates and welding, differences in paint thickness and quality, water temperature, salinity and aeration all combine to cause areas of the hull to become either anodic (positive) or cathodic (negative).

Figure 5.9 shows that, in the hull, electrons flow from anode to cathode leaving positively charged iron ions at the anodic area. At the cathode, the effect of the arrival of electrons is to produce negatively charged hydroxyl ions (OH) by electrolysis of the seawater. These negative ions flow through the sea to the anodic area where they combine with the positive iron ions to form ferrous hydroxide $Fe(OH)_2$. This ferrous hydroxide is further oxidised by dissolved oxygen to form ferric hydroxide $Fe(OH)_3$ which is rust. In this way, the anodic area is gradually corroded away while no corrosion takes place at the cathodic area.

This naturally corrosive action can be overcome if the complete hull is made cathodic, ie electrons are allowed to arrive at the hull surface and produce negative hydroxyl ions but no electrons leave the hull to produce positive iron ions. This is achieved by fitting insulated lead or platinised titanium anodes to the hull and applying a positive DC potential to them with respect to the hull.

The negatively charged OH ions now pass to the insulated lead anodes causing the lead surface to change to lead peroxide PbO_2. The potential is of such a value that it just overcomes the original corrosion current and gives rise to an impressed protection current that flows in the complete circuit. The value of protection current must be critically controlled to just prevent corrosion, as beyond this value the increase in the rate of release of OH ions will cause sponginess and flaking of the anti-fouling paint.

Initially, the electrolytic action will form PbO_2 on the surface of the anodes and when this skin is formed the action reduces. The anodes take on a rich brown appearance (positive lead-acid battery plate) and in service are expected to last 7-10 years.

The correct value of protection current can be determined by reference electrodes. These are either of zinc or silver attached to the hull, but insulated from it, below the waterline.

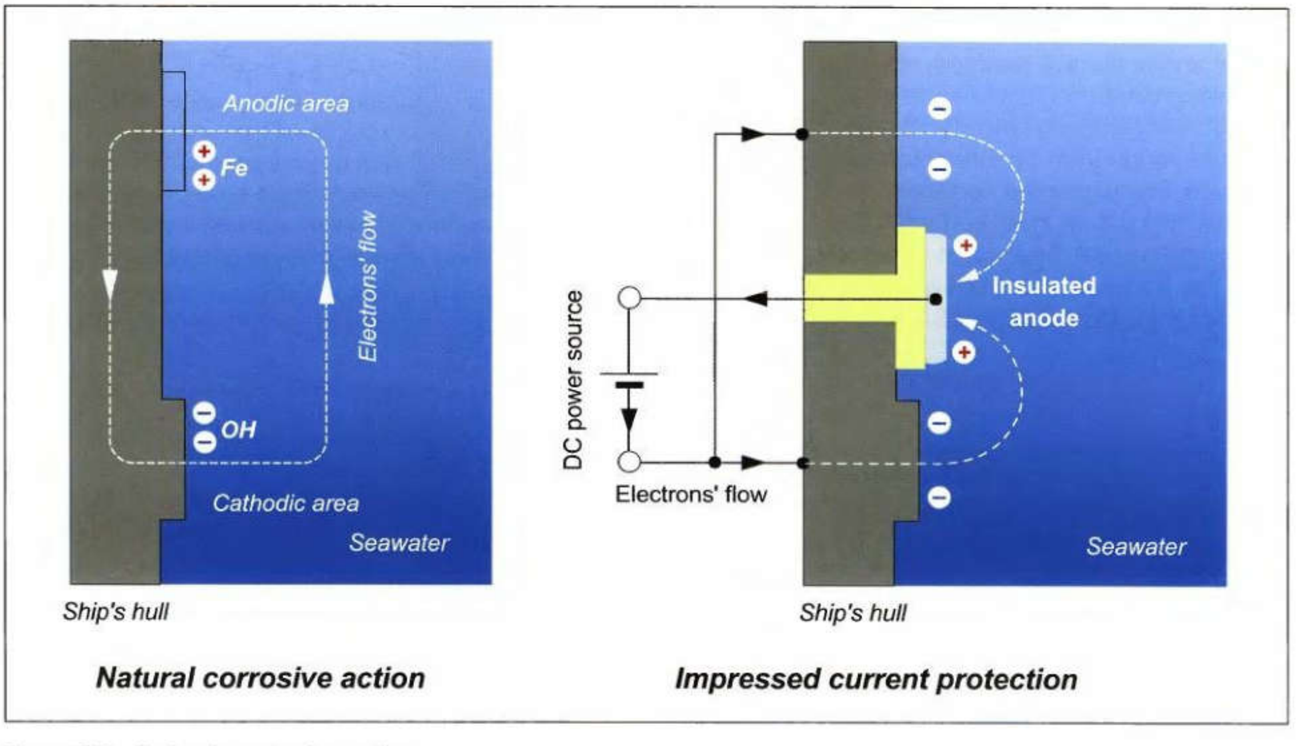


Figure 5.9 - Cathodic protective action

The voltage measured between the hull and reference electrodes of an unprotected ship with seawater as an electrolyte is:

Zinc electrode	450 mV negative to hull
Silver electrode	600 mV positive to hull

When satisfactorily protected, the protection current will make the hull 200 mV more negative, ie a zinc reference electrode will register 250 mV negative to hull and silver 800 mV positive to hull, as shown in Figure 5.10. The reference electrode voltage may, therefore, be used to monitor the protection, but more importantly, it is used as the signal source to automatically regulate the value of protection current.

Cathodic protection systems fitted in ships consist of a number of anodes (lead or platinised titanium) fitted to the hull, at selected places below the waterline and control equipment, that automatically regulate the anode current to the required value. Direct current is supplied to the anodes, after transformation and rectification, from the ship's 440 V 60 Hz three-phase AC distribution system. The control equipment comprises reference electrodes, an amplifier assembly and one or more transformer rectifier units.

The anode current control is usually regulated by electronic thyristor controllers and the diagram in Figure 5.11 outlines a typical scheme.

The control equipment automatically monitors the size of anode current required, which will vary with the ship's speed, water temperature and salinity, condition of paintwork, etc. Typical anode current densities range from 10 mA/m^2 to 40 mA/m^2 for the protection of painted surfaces, and 100 to 150 mA/m^2 for bare steel surfaces. The total impressed current for a hull in good condition may be as low as 20 A. Maximum controller outputs may be up to about 600 A at 8 V.

Cathodic protection does not appear to deter mollusc growth on the ship's hull, so a top coat of anti-foul (poisonous) paint is still necessary.

Typical reference and main anode outlines are shown in Figure 5.12.

Monitoring facilities in the cathodic protection control cabinet may provide measurements of:

- Reference electrode voltage (hull potential)
- amplifier output voltage
- total anode current
- individual anode current.

Changes in the underwater hull area, speed, water temperature/salinity and paint condition will all cause the anode currents to vary. The hull potential should, however, remain constant in a properly regulated system.

Although the reference electrodes and the monitoring facilities provide a reasonable day-to-day check, they are only measuring in the vicinity of the fitted electrodes.

When the ship is moored singly or stopped at sea, voltage readings can be taken between a portable silver or zinc test electrode and the ship's hull. This portable electrode is lowered 2-3 metres below the water surface and as close as possible to the hull at specified positions around the ship.

Check the manufacturer's instructions regarding the storage and setting up of the portable electrode. Some have to be immersed in a plastic bucket of seawater for about 4 hours before the hull test. With the cathodic protection switched on and working normally, the voltage measured between the hull and a silver/silver chloride portable electrode should be 750-850 mV using

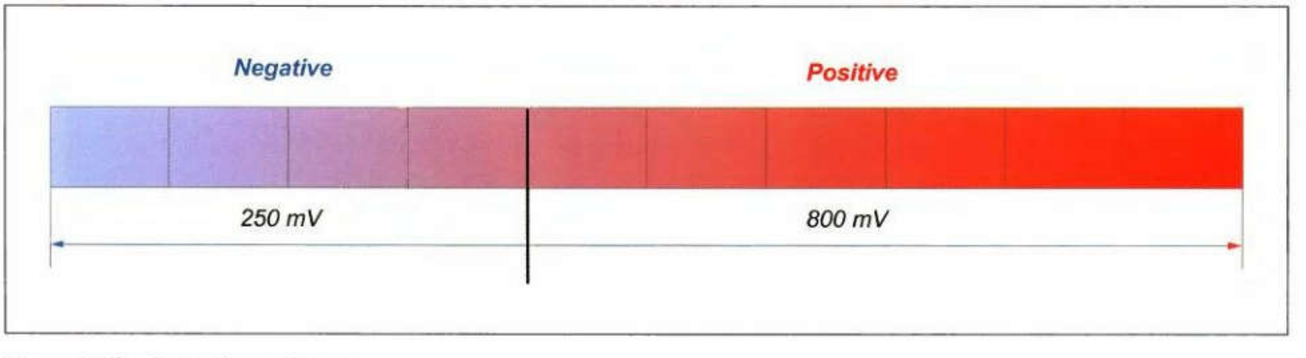


Figure 5.10 - Protection voltages

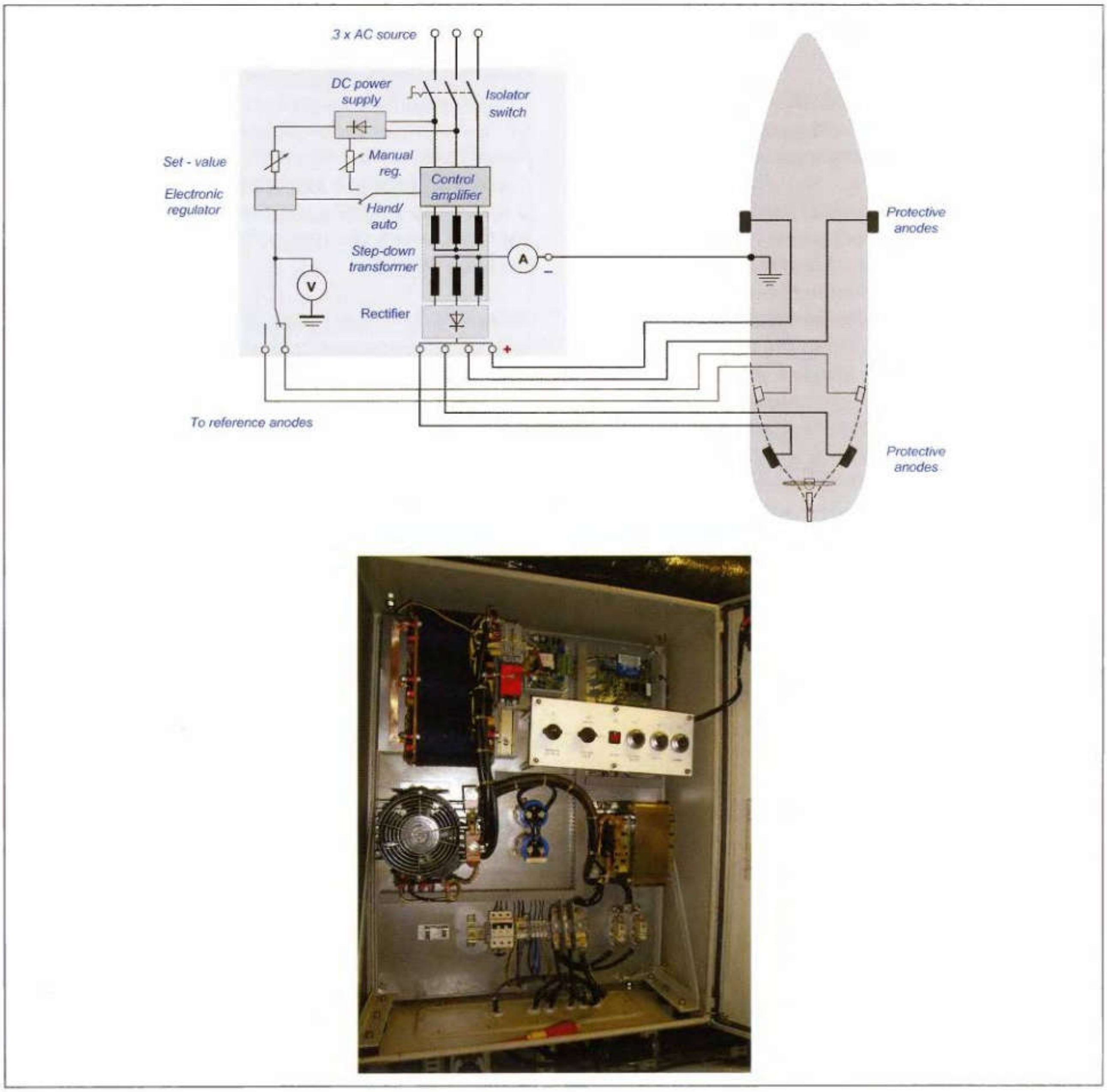


Figure 5.11 - Ship anodes and impressed current control system

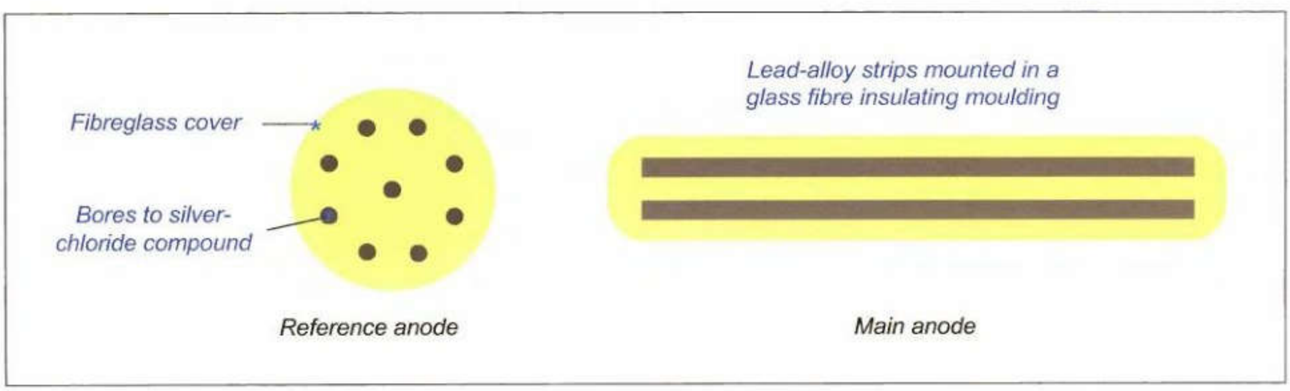


Figure 5.12 - Reference and main anode construction

a multimeter, the electrode being positive with respect to the hull.

When dry docked, ensure that the main anodes and reference electrodes are covered with paper tape to prevent paint contamination.

To ensure that the rudder and propeller screw (and stabiliser fins for ferries and passenger ships) receive the same degree of cathodic protection as the hull, it is necessary to electrically earth bond these items to the hull. The rudder stock may be bonded by a wire braid linking the top of the stock to the deckhead directly above it. Carbon brushes rubbing on the rotating main propulsion shaft effectively bond the shaft to the hull. A periodic inspection of such earthing is worthwhile as the brushes wear away and may occasionally stick in their brush holders.

5.5 Battery Supplies

A properly maintained storage battery will instantly supply electric power when required. This feature makes a battery the key element in the provision of essential and emergency power supplies on board ships.

Essential routine power supplies, eg for radio equipment, telephone exchange, fire detection, general alarm circuits, etc, are often supplied from a set of batteries worked on a regular charge/discharge cycle.

Emergency battery supplies, eg for emergency generator startup and emergency lighting, are used in a standby role to give power when the main supply fails. Ships' batteries are usually rated at a nominal voltage of 24 V DC.

The two main types of rechargeable battery cell are:

- Lead-acid
- alkaline.

The nominal cell voltages of each type are 2 V for lead-acid and 1.2 V for alkaline. Twelve lead-acid cells or twenty alkaline cells must be connected in series to produce a nominal 24 V. More cells may be connected in parallel to increase the battery capacity, which is rated in ampere-hours (Ah). The battery capacity is usually rated in terms of its discharge at the 10 hour rate. A 350 Ah battery would be expected to provide 35 A for 10 hours. However, the battery will generally have a lower capacity at a shorter discharge rate. The manufacturer's discharge curves must be checked for such details.

After a 10 hour discharge, a lead-acid cell voltage will have fallen to approximately 1.73 V. The equivalent figure for an alkaline cell is 1.14 V.

Battery installations for both types of battery are similar in that the battery room should be well ventilated, clean and dry. Both types generate hydrogen gas during charging, so smoking and naked flames must be prohibited in the vicinity of the batteries.

Steelwork and decks adjacent to lead-acid batteries should be covered with acid-resisting paint. Alkali-resisting paint should be used near Ni-cad cells.

Acid cells must never be placed near alkaline cells because of the risk of rapid electrolytic corrosion to metalwork and damage to both batteries. For similar reasons, never use lead-acid battery maintenance gear (eg hydrometer, topping up bottles, etc) on an alkaline installation, or vice versa.

Battery maintenance includes keeping the cell tops clean and dry, checking the tightness of terminal nuts and applying a smear of petroleum jelly to connections to prevent corrosion.

Be careful when handling the battery electrolyte (eg when using a hydrometer to check its specific gravity). Use protective rubber gloves and eye goggles when handling electrolyte. Insulated spanners should be available for use on cell connections to prevent accidental short-circuiting of battery terminals. A short-circuit across the terminals of just one cell of a battery will cause a blinding flash, with the probability of the cell being seriously damaged.

QUESTION

An alkaline cell has an electrolyte of potassium hydroxide while a lead-acid cell uses sulphuric acid. Both are diluted with distilled water.

What first aid treatment would you apply should you be splashed with either electrolyte?

ANSWER

In both cases, rapidly wash eyes and skin with plenty of fresh water. The electrolyte of alkaline cells causes skin burns that should be treated with boracic powder and the eyes washed out with a solution of boracic power - one teaspoonful to a pint of water.

Sulphuric acid splashes can be washed with a saline solution – two teaspoonfuls of household salt to one pint of water.

For both types of battery, first aid equipment should be in the battery compartment.

Figure 5.13 shows the principal features of a lead-acid cell.

The state of charge held by a lead-acid battery is best indicated by a test on the electrolyte specific gravity (SG), by using a hydrometer, as shown in Figure 5.14. A fully charged lead-acid cell has an SG of about 1.27-1.285 (often written as 1270-1285), which falls to about 1.1 (or 1100) when fully discharged. The cell voltage also falls during discharge and its value can also be used as an indication of the state of charge.

A lead-acid battery may be safely discharged until the cell voltage drops to approximately 1.73 V (measured while delivering load current).

The open circuit (no load) battery voltage readings can be misleading as a high value does not necessarily indicate that the cells are in a healthy charged state. Note that the SG values quoted above for lead-acid cells are based on an ambient temperature of 15°C. Corrections to the SG value at any other ambient temperature are:

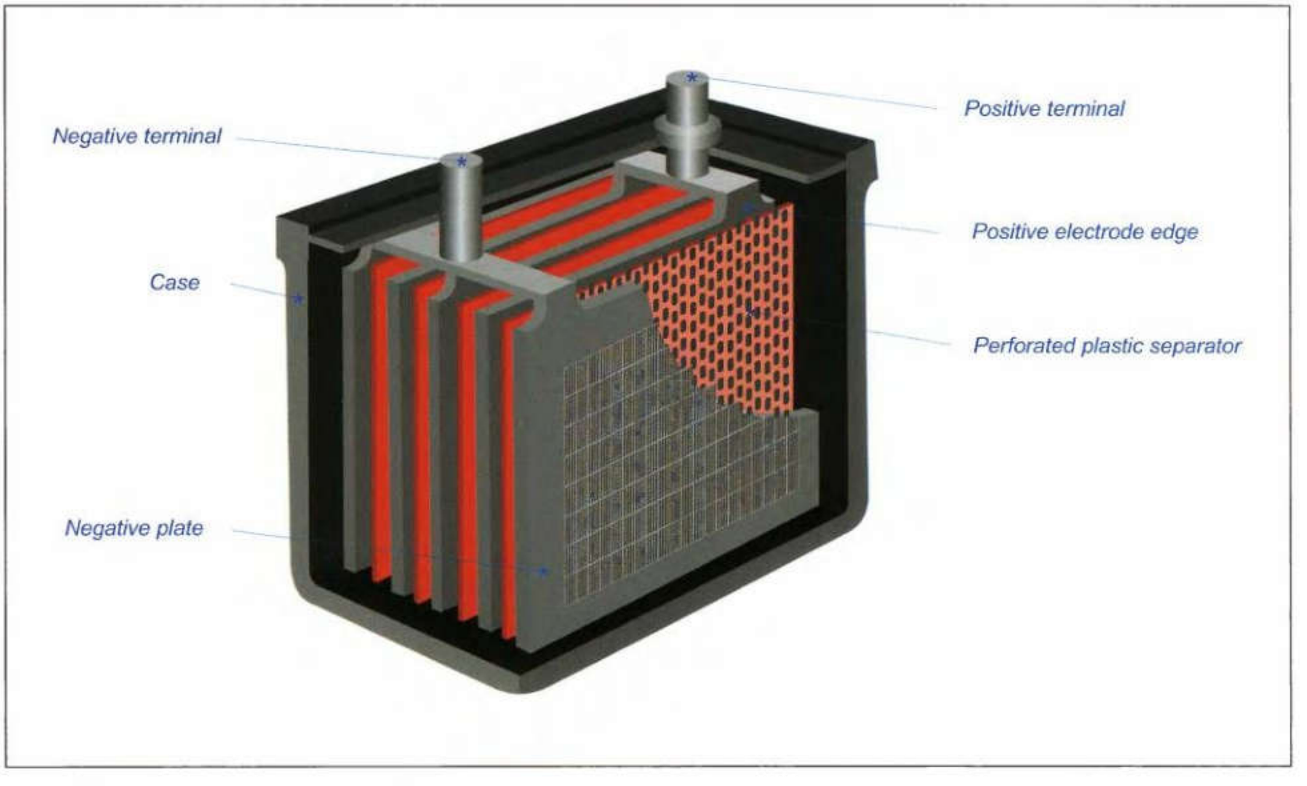


Figure 5.13 - Lead-acid cell construction

- Add 0.007 to reading for each 10°C above 15°C
- subtract 0.007 from reading for each 10°C below 15°C.

Figure 5.15 outlines the principal features of an alkaline cell.

The state of charge of an alkaline battery cell cannot be determined from its SG value. The electrolyte density does not change during charge/ discharge cycles, but gradually falls during the lifetime of the battery.

New alkaline cells have an SG of around 1190. When this reduces to about 1145 (which may take 5-10 years depending on the duty cycle), the electrolyte must be completely renewed or the battery replaced. Discharge of alkaline cells should be discontinued when the cell voltage has fallen to about 1.1 V.

Figure 5.14 - Hydrometer testing

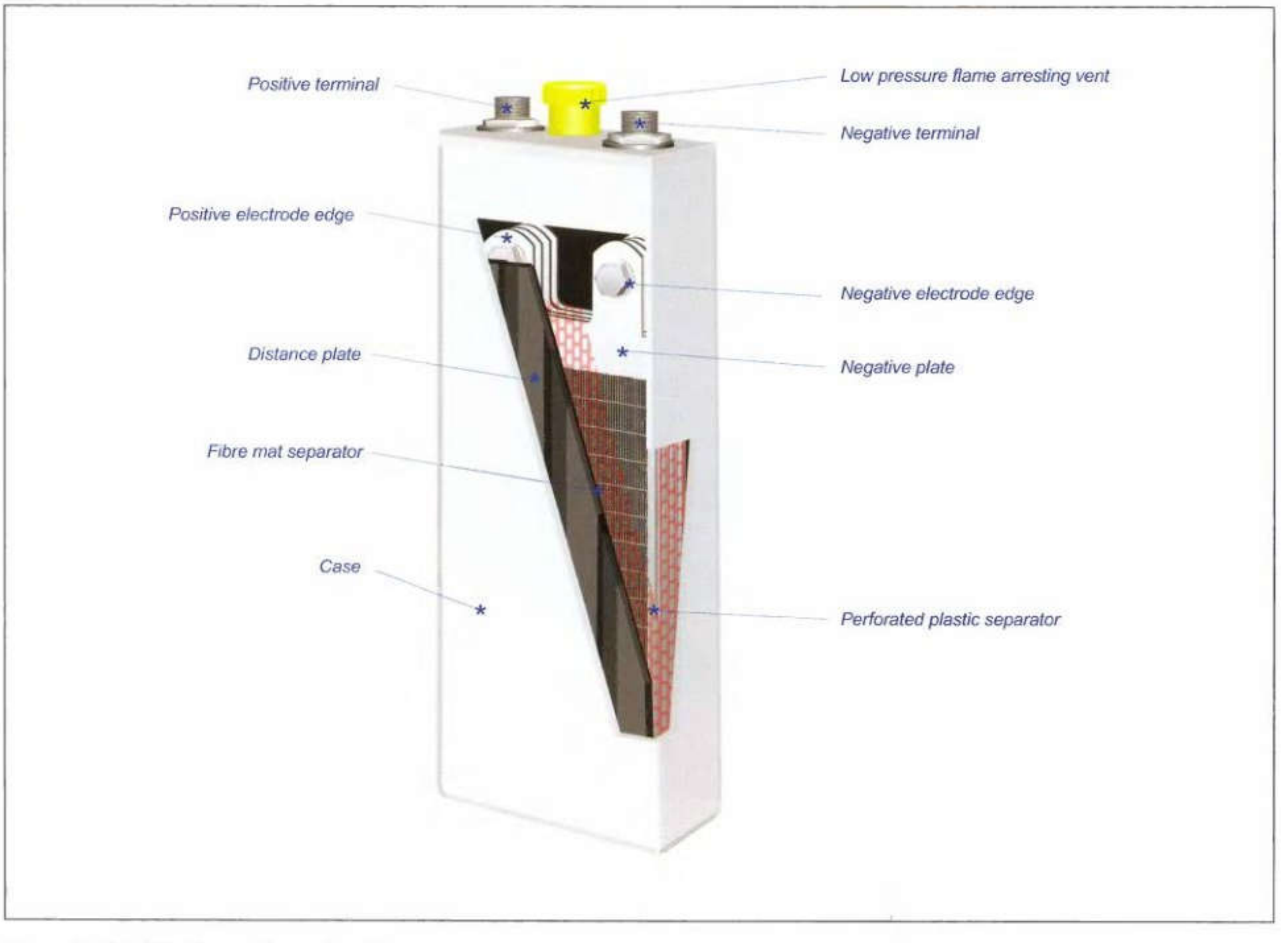


Figure 5.15 - Alkaline cell construction

Battery charging equipment uses a transformer/rectifier arrangement to supply the required DC voltage to the cells. The size of voltage depends on the battery type (lead-acid or alkaline) and the mode of charging, eg charge/discharge cycle, boost charge, trickle or float charge. Check the manufacturer's instructions for details of the required charging voltages.

Do not allow electrolyte temperatures to exceed about 45°C during charging. A lead-acid cell will gas freely when fully charged, but an alkaline cell gases throughout the charging period. The only indication of a fully charged alkaline cell is when its voltage remains at a steady maximum value of about 1.6-1.8 V.

Generally, alkaline cells are more robust, mechanically and electrically, than lead-acid cells. Nickel-cadmium cells will hold their charge for long periods without recharging so are ideal for standby duties. They also operate well with a float charge to provide a reliable emergency supply when the main power fails.

For all rechargeable batteries (other than the sealed type), it is essential to replace lost water (caused during gassing and by normal evaporation) with the addition of distilled water to the correct level above the plates. Exposure of the cell plates to air will rapidly reduce the life of the battery.

On all ships and offshore platforms, there are essential services that are vital during a complete loss of main power. Such services include switchgear operation, navigation lights, foghorns, fire and gas detection, internal communications, some radio communications and alarm systems. To avoid the loss of essential services, they are supported by an uninterruptible power supply or UPS. These can be for battery-supported DC supplies or AC supplies, both of which can be configured as continuous UPS or standby UPS. Figure 5.16 shows an AC-supported UPS arrangement.

The arrangement shown in Figure 5.17 is typical of a continuous UPS DC-supported supply system. The essential DC services are normally supplied from the 440 V main power system through charger no. 1 which continuously trickle charges its battery. During a loss of main power, battery no. 1 maintains a transitional supply while the emergency generator restores power to the emergency board and so to charger no. 2. Either battery is available for a few hours if both main and emergency generators are unavailable.

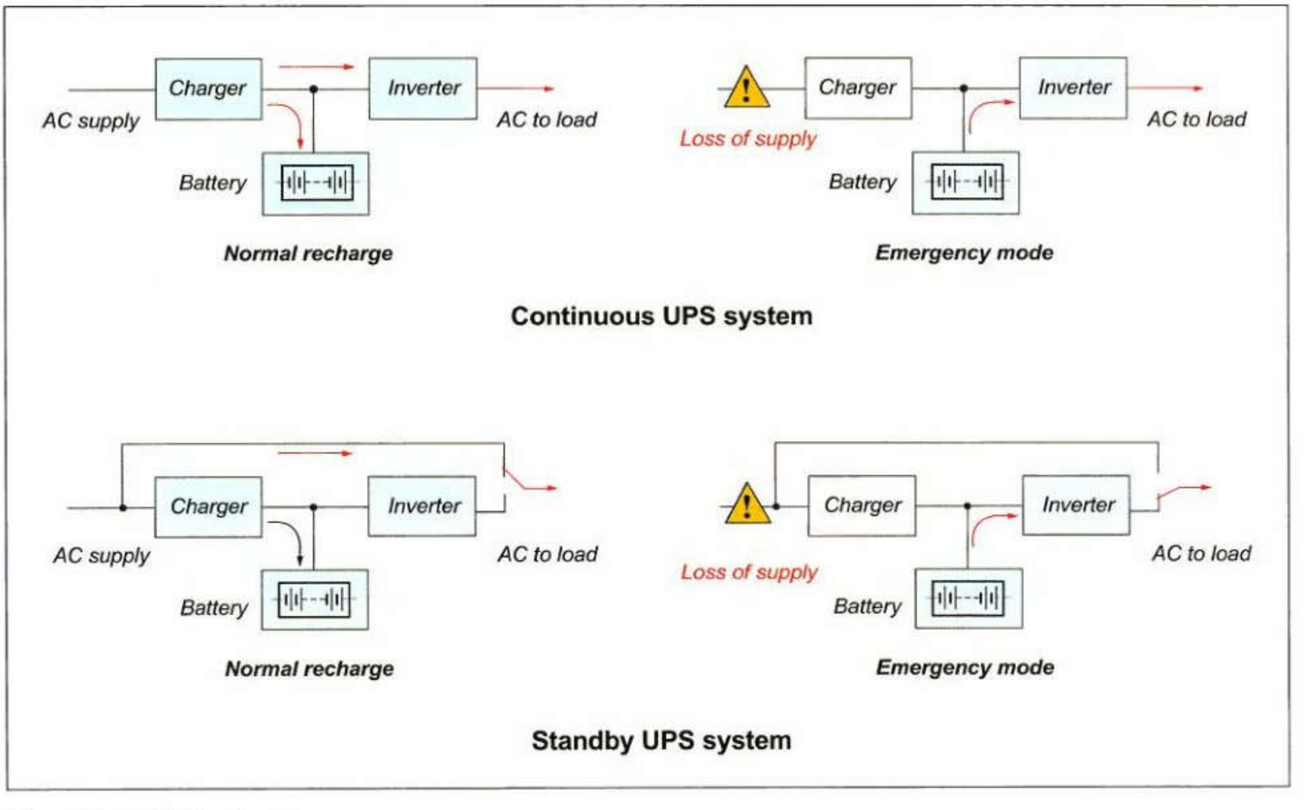


Figure 5.16 - UPS systems

Some critical emergency lights have an internal battery-supported UPS within the luminaire, where its battery charge is continuously maintained during non-emergency conditions.

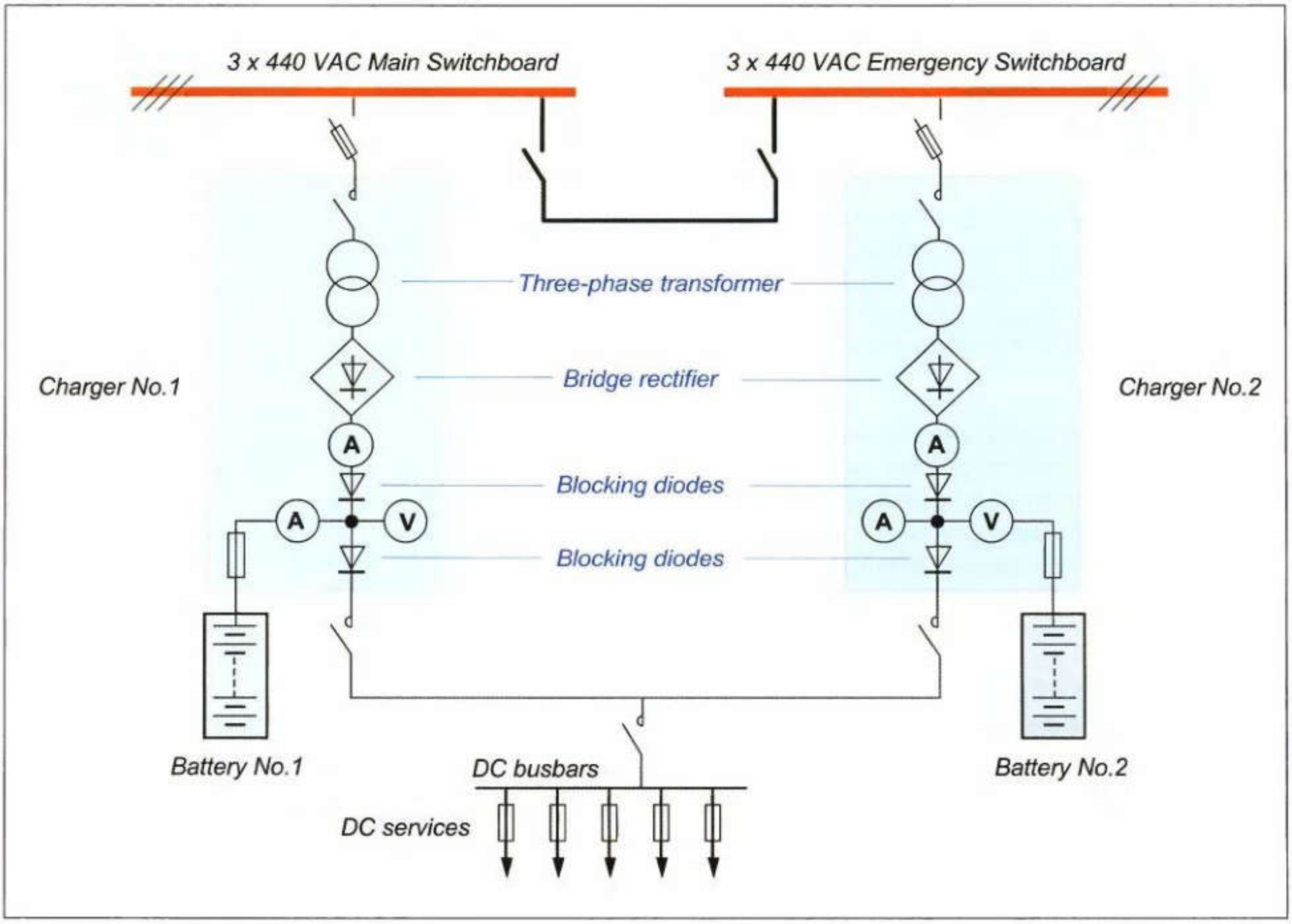


Figure 5.17 - UPS DC battery charger

Chapter Six
Special Electrical Practice for Hazardous Atmospheres

The safety intent of a design may be ruined by poor maintenance practice.

Maintenance must not cause the operation of electrical equipment to be in a less safe condition than it was in its original certified state.

> This means that maintenance must be carried out by a competent person. Temporary arrangements, refitting with the wrong sized components (eg lamps), failing to employ the correct number of cover bolts, etc are absolutely forbidden.

Ships and offshore installations that transport, process and store bulk quantities of oil, gas and liquid chemicals are subject to special electrical codes of practice. Statutory Authorities and Classification Societies generally base their recommendations on the International Electrotechnical Commission (IEC) standard 60092 '*Electrical Installations on Ships*'.

Spaces in tankers where explosive gas/air mixtures may be expected to be present are called dangerous or hazardous. While all other areas being regarded as 'safe', special care will always be required on any vessel carrying hazardous cargoes.

The best way to avoid explosions caused by electrical equipment is to not install such equipment in the hazardous areas. However explosion (Ex) protected equipment is permitted where it is necessary, and this chapter will consider where and how it is used and how it should be maintained.

6.1 Hazardous Zones on Tankers

Petroleum and chemical industry practice for hazardous areas is to divide them into three zones (0, 1 and 2) that recognise the degree of hazard and indicate the likelihood of an explosive gas-air mixture being present.

Zone 0

An area in which an explosive gas atmosphere is present continuously or for long periods.

Zone 1

An area in which an explosive gas atmosphere is likely to occur in normal operation.

Zone 2

An area in which an explosive gas atmosphere is not likely to occur in normal operation and, if it occurs, will only exist for a short time.

An area not classified Zone 0, 1 or 2 is assumed to be a non-hazardous or safe area.

While this practice is not used on tankers, electrical equipment is manufactured and graded largely on the basis of such zones.

In addition, when a tanker is alongside, parts of it may fall into the hazardous zones of the shore facility, possibly in areas of the ship that may not normally be considered unsafe.

On tankers, areas are designated as either *dangerous* or *normally-safe* spaces.

A *dangerous* space is an area where flammable gas-air or vapour mixtures might normally be expected to occur.

Examples of the industry style zoning when applied to ships could be:

Zone 0

Interior spaces of oil cargo tanks, pipes, pumps, etc.

Zone 1

Enclosed or semi-enclosed spaces on the deck of a tanker, the boiler firing area on a gas carrier using methane boil-off as a fuel and battery rooms.

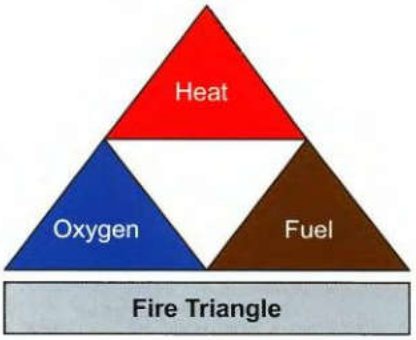
Zone 2

Open spaces on the deck of a tanker (although this may change when alongside).

6.2 Understanding the Fire Triangle

Before a fire or explosion can take place, the three elements that must be present, commonly referred to as the 'fire triangle', are:

- A flammable material capable of supporting combustion (fuel)
- source of ignition with sufficient energy to initiate combustion (heat)
- an adequate supply of oxygen, usually air (oxidiser).



The removal of any of the elements will prevent or extinguish a fire.

When a flammable material is mixed with air, there needs to be a certain concentration of fuel (flammable substance) within the mixture for it to burn (making it the fuel element of the fire triangle). The flammable range is the range of concentrations of a particular substance within air that may catch fire or explode. For example, a mixture of hydrocarbon gas and air cannot ignite and burn unless its composition lies within the flammable range. The proportion of combustible material in the mixture is expressed as a percentage by volume of vapour in air, and is delineated by the upper and lower flammable limits.

Lower flammable limit (LFL)
Lower explosive limit (LEL)
Below the lower limit of the flammability range, known as the lower flammable limit (LFL), there is insufficient flammable material in the mixture to support combustion. The LFL refers to the leanest mixture that can sustain a flame.

Upper flammable limit (UFL)
Upper explosive limit (UEL)
The upper flammable limit (UFL) refers to the point above which there is insufficient air to generate or support combustion. The UFL gives the richest flammable mixture.

Using inert gas in tanks and pipes keeps the atmosphere within them outside of the flammable zone (Table 6.1).

Substance	Lower Flammable Limit (LFL)	Upper Flammable Limit (UFL)
Acetylene	*2.3 vol. %*	*78.0 (self-decomposing) vol. %*
Ethylene	*2.3 vol. %*	*32.4 vol. %*
Petroleum spirit	*~0.6 vol. %*	*~8 vol. %*
Benzene	*1.2 vol. %*	*8 vol. %*
Natural gas	*4.0 (7.0) vol. %*	*13.0 (17.0) vol. %*
Heating oil/diesel	*~0.6 vol. %*	*~6.5 vol. %*
Methane	*4.4 vol. %*	*16.5 vol. %*
Propane	*1.7 vol. %*	*10.9 vol. %*
Carbon disulfide	*0.6 vol. %*	*60.0 vol. %*
City gas	*4.0 (6.0) vol. %*	*30.0 vol. %*
Hydrogen	*4.0 vol. %*	*77.0 vol. %*

Table 6.1 - Common substance flammable limits

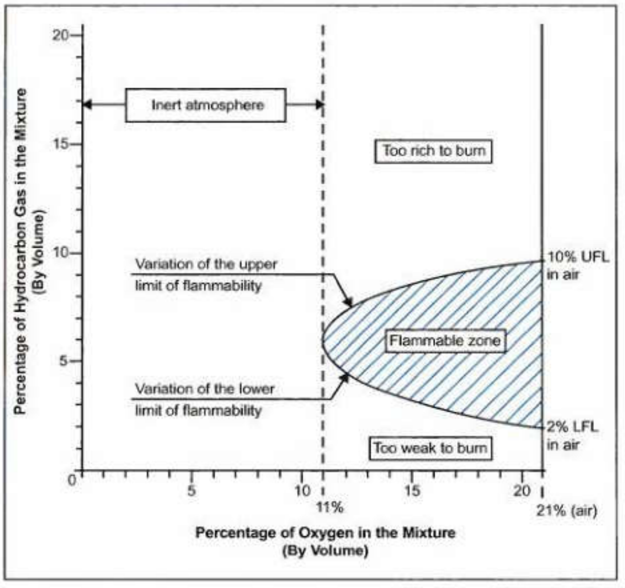


Figure 6.1 - Oxygen content in a hydrocarbon/air mixture

This example shows us that, for a hydrocarbon gas/oil mixture, once the limiting oxygen concentration is reached combustion is not possible despite the presence of sufficient fuel.

Finally, it is also necessary for ignition (the last part of the triangle) to take place.

Minimum ignition energy (MIE) is the minimum amount of energy required to ignite a combustible vapour, gas or dust cloud, for example by means of an electrostatic discharge.

The auto-ignition temperature, or kindling point, of a substance is the lowest temperature at which it will spontaneously ignite in a normal atmosphere without an external source of ignition, such as a flame or spark.

Examples of these temperatures are:

Gas	Auto-Ignition Temperature (°C)	Minimum Ignition Energy (mJ)
Acetylene	305	0.02
Butane	365	0.25
Hydrogen	560	0.02
Methane	595	0.29

Table 6.2 - Auto-ignition temperatures

Table 6.2 shows that hydrogen has a very low ignition energy, but a very high ignition temperature. Acetylene, however, has a low ignition energy and low ignition temperature (so it is very easy to ignite). Methane, with its very high ignition temperature and high ignition energy, can be surprisingly difficult to ignite.

Therefore, we can see that it is possible that gases or vapours, when concentrated between their UFL and LFL limits and in the presence of air, might be ignited by heat generated from various electrical sources, such as:

- Arcing between switch contacts
- arcing between a live conductor and earth
- an internal arcing fault within an electrical enclosure
- overheating causing hot spots
- an electrostatic spark discharge between charged bodies or between a charged body and earth.

6.3 Explosion Groups and Temperature Classes

Explosion Groups

The flammable gases in which explosion-protected electrical equipment may have to operate are grouped according to the amount of electrical energy, in the form of an arc, that is needed to ignite the gas. This classification determines the safety gap needed between the flameproof enclosure and its cover to ensure that sufficient energy does not cross.

The gases associated with the mining industry are fire-classed as GROUP **I**. All other industrial gases are classed as GROUP **II** and these are split into three sub-groups according to their ease of ignition.

Group IIC is the most severe group. Gases in this group can be very easily ignited. Electrical equipment certified as suitable for Group IIC is also suitable for IIB and IIA. Equipment certified as suitable for IIB is also suitable for IIA but not for IIC. Equipment certified for IIA may not be used with groups IIB or C.

Equipment Group	Use	Explosion Group	Safety Gap for Flameproof Enclosure
Group I	Electrical equipment for mines Fire damp protection EEx...I		
Group II	Electrical equipment for areas endangered by explosive gases Explosion protection Ex...II	IIA IIB IIC	>0.9 mm 0.5 mm to 0.9 mm <0.5 mm

Table 6.3 - Explosion Groups

The gas grouping is another factor that will affect the design and construction of equipment to be used in hazardous zones. Section 6.4 explains the ratings used and what they mean in more detail.

Temperature Classes

As well as considering the protection against electrical arc and sparks igniting a flammable atmosphere, consideration must be given to the surface temperature of equipment because most electrical apparatus dissipate some heat.

The ignition temperature of flammable gases or a flammable liquid is the lowest temperature of a heated surface at which the gas/air or vapour/air mixture ignites. Therefore, the highest surface temperature of any equipment must always be less than the ignition temperature of the surrounding atmosphere.

The temperature class is the maximum surface temperature of the components in the electrical equipment under normal and fault conditions. It is stated with reference to a maximum ambient temperature of 40°C; should any other reference temperature be adopted, regulations require that this temperature be shown on the equipment.

It is important to note that the apparatus gas grouping and temperature class are not related. For instance, hydrogen requires very little spark energy to ignite, but the surface temperature necessary for ignition is very high (560°C).

Temperature classes T1 to T6 have been introduced for electrical equipment rated within explosion group II.

T- Class IEC/EN NEC 505-10	T Class NEC 503-3 CEC 18-052	Maximum Surface Temperature of Equipment	Ignition Temperatures of Flammable Substances
T1	T1	450°C	>450°C
T2	T2	300°C	>300 ≤450°C
	T2A	280°C	>280 ≤300°C
	T2B	260°C	>260 ≤280°C
	T2C	230°C	>230 ≤260°C
	T2D	215°C	>215 ≤230°C
T3	T3	200°C	>200 ≤300°C
	T3A	180°C	>180 ≤200°C
	T3B	165°C	>165 ≤180°C
	T3C	160°C	>160 ≤165°C
T4	T4	135°C	>135 ≤200°C
	T4A	120°C	>120 ≤135°C
T5	T5	100°C	>100 ≤135°C
T6	T6	85°C	>85 ≤100°C

Table 6.4 - Temperature classes and related ignition temperatures

Temperature class relates to all parts of the equipment that can come into contact with potentially explosive atmosphere.

The bigger the T-number, the lower the temperature. The temperature classification will be marked on items of equipment. If the hazardous area in which you are installing equipment has gases or vapours with a low auto-ignition temperature then you will need equipment with a bigger T-number to ensure that any hot surfaces on the equipment will not ignite the hazard.

As an example, an electric motor may have a maximum surface temperature of 120°C and would be classed as T4.

6.4 Explosion Protection

Integrated explosion protection requires all explosion protection measures to be carried out in a defined order.

Primary explosion protection covers all measures that prevent a potentially explosive atmosphere forming. These include:

- Inerting (the addition of nitrogen, carbon dioxide, etc)
- limiting concentrations
- ventilation.

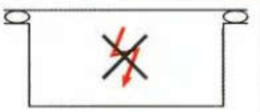
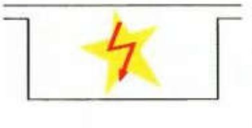
If the explosion hazard cannot be removed then specifically designed and rated electrical equipment must be used.

Electrical equipment for hazardous areas must comply with the general requirements of EN 60079-0. All types of protection are based on different protection concepts.

Explosion is identified by the symbol 'Ex' followed by a letter indicating the type of protection employed.

Figure 6.2 - European Ex identification mark

Protection types for electrical equipment in explosive gas atmospheres are:

Type of Protection General Requirements	Marking	Schematic Diagram Symbol	Basic Principle	Standard	Examples
General requirements			General requirements for the type and testing of electrical equipment intended for the Ex area	EN 60079-0 IEC 60079-0	
Increased safety	e		Applies only to equipment, or its component parts, that normally does not create sparks or arcs, does not attain hazardous temperatures, and whose mains voltage does not exceed 1 kV	EN 60079-7 IEC 60079-7	Terminals, terminal boxes
Flameproof enclosure	d		If an explosion occurs inside the enclosure, the housing will withstand the pressure and the explosion will not be propagated outside the enclosure	EN 60079-1 IEC 60079-1	Switchgear, transformers

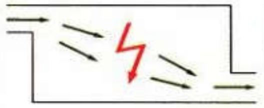
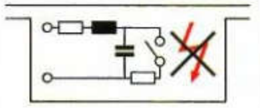
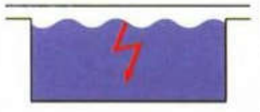
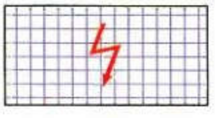
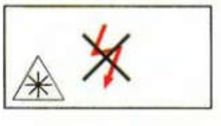
Pressurised enclosure	p		The ignition source is surrounded by a pressurised protective gas (min. 0.5 mbar) – the surrounding atmosphere cannot enter	EN 60079-2 IEC 60079-2	Control cabinets, switchgear cabinets
Intrinsic safety	i		By limiting the energy in the circuit, the formation of impermissibly high temperatures, sparks, or arcs is prevented	EN 60079-11 IEC 60079-11	Actuators, sensors, PROFIBUS DP RS 485-iS
Oil immersion	o		Equipment or equipment parts are immersed in oil and therefore separated from the Ex atmosphere	EN 60079-6 IEC 60079-6	Transformers switching devices
Quarz filling (Sand filling)	q		Ignition source is buried in granular packing material (eg sand). The Ex atmosphere surrounding the housing cannot be ignited by an arc	EN 60079-5 IEC 60079-5	Strip heaters, capacitors
Encapsulation	m		By encapsulation of the ignition source in a moulding, it cannot ignite the Ex atmosphere	EN 60079-18 IEC 60079-18	Sensors, switching devices
Type-n protection (Non-sparking)	n		Slightly simplified application of the other protection types – 'n' stands for 'non-igniting'	EN 60079-15/2/18/11 IEC 60079-15/2/18/11	PLCs
Optical radiation	op		Suitable measures prevent a hazardous atmosphere from being ignited by optical radiation.	EN 60079-28 IEC 60079-28	Fibre optic conductors

Table 6.5 - Classification of explosion proof equipment

6.5 Exd Flameproof Enclosure

Type 'd' protection, code Exd (for group II), uses a flameproof enclosure to contain the electrical apparatus. The internal apparatus may include parts that arc and surfaces that become hot. Gas may be inside the enclosure, so it must fulfil three conditions:

- The enclosure must be strong enough to withstand an internal explosion without suffering damage
- the enclosure must prevent the flame and hot gases from being transmitted to the external flammable atmosphere
- the external surface temperature of the enclosure must remain below the ignition temperature of the surrounding gas under all operating conditions.

The transmission of flame and hot gases from a flameproof enclosure is prevented because all joints, such as flanges, spigots, shafts and bearings, are closely machined to achieve a gap that is less than a defined maximum. The pressure of an internal explosion is then released through the small gap between the machined faces, which cools the gas sufficiently to prevent it from igniting any external flammable atmosphere.

The maximum permitted gap depends upon three factors:

- The type of gas with which the apparatus is safe for use.
- the width of the joint (L)
- the volume of the enclosure (V).

QUESTION

A ship's battery room is fitted with a flameproof luminaire marked 'Exd IIC T4'. Is this luminaire certified for use in the battery room?

ANSWER

Yes.
The hazard is hydrogen gas from the batteries which requires apparatus designed for use in apparatus gas group IIC. The ignition temperature of hydrogen is 560°C and the temperature classification of the luminaire is T4. This means that its surface temperature will not exceed 135°, so the temperature classification is satisfactory.

The cable entry into an Exd enclosure must also be maintained flameproof by using a certified Exd gland. This type of gland, shown in Figure 6.4, has a compound filling that forms a barrier between the individual conductors and prevents entry of explosive products from the enclosure entering the cable.

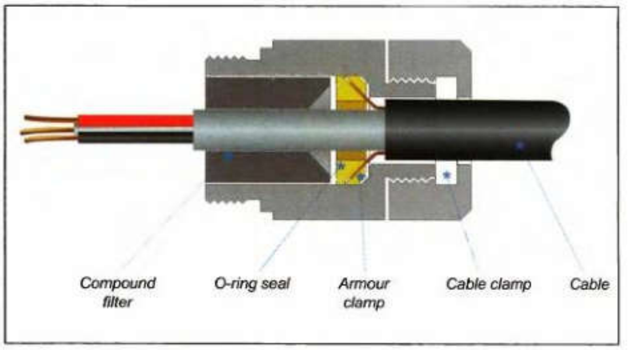


Figure 6.4 - Exd cable gland

6.6 Exi Intrinsic Safety

The intrinsic safety of a circuit is achieved by limiting the current and voltage. This limits the type to circuits with a relatively low power, such as that used for measuring or control.

In an intrinsically-safe circuit, no sparks or thermal effects occur in operation, or even in the event of a fault.

Generally, intrinsic protection means limiting the circuit conditions to less than 30 V and 50 mA.

The design of the circuit will depend on the type of gas expected to be present (gas grouping). Two grades of intrinsic safety are recognised:

- Exia, the highest category based on a safety factor of 1.5 with two faults on the circuit
- Exib, based on a safety factor of 1.5 with one fault on the circuit.

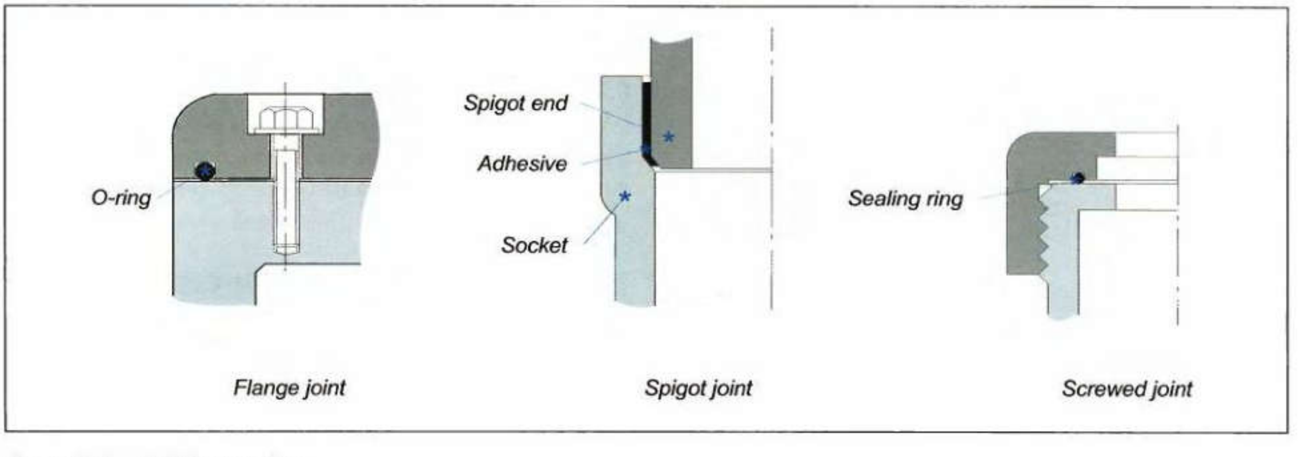


Figure 6.3 - Exd flamepaths

An important measure for intrinsically safe circuits is their safe isolation from non-intrinsically safe circuits. Safe electrical isolation is always required, with the exception of safety barriers. Electric isolation is generally recommended for Zone 0.

Zener diodes, used for limiting voltage as well as other semi-conductor components, are considered to be fallible and must be safeguarded by redundant components. Wire wound or sheet resistors for current limitation are considered to be infallible components (as they have high resistivity in the event of a fault), so only one component is sufficient.

The purpose of a zener barrier is to limit voltages and currents in the hazardous area when faults occur on the circuit.

A separate barrier is required for each Exi circuit and they must be fitted outside the hazardous area (see Figure 6.5).

A safety (or zener) barrier comprises:

- A fuse to limit the maximum current through the shunt (zener) diodes
- a set of resistors to limit the maximum current into the hazardous area
- a set of shunt-connected zener diodes to limit the maximum voltage appearing on the circuit within the hazardous area.

All components are sealed into a compact package with clearly marked terminals at each end of the barrier.

The circuit in Figure 6.6 shows a single-channel zener barrier. It illustrates the preventive action in the event of a high voltage being accidentally applied to the non-hazardous terminals.

The zener diode, when connected with reverse bias, has an approximately constant voltage across

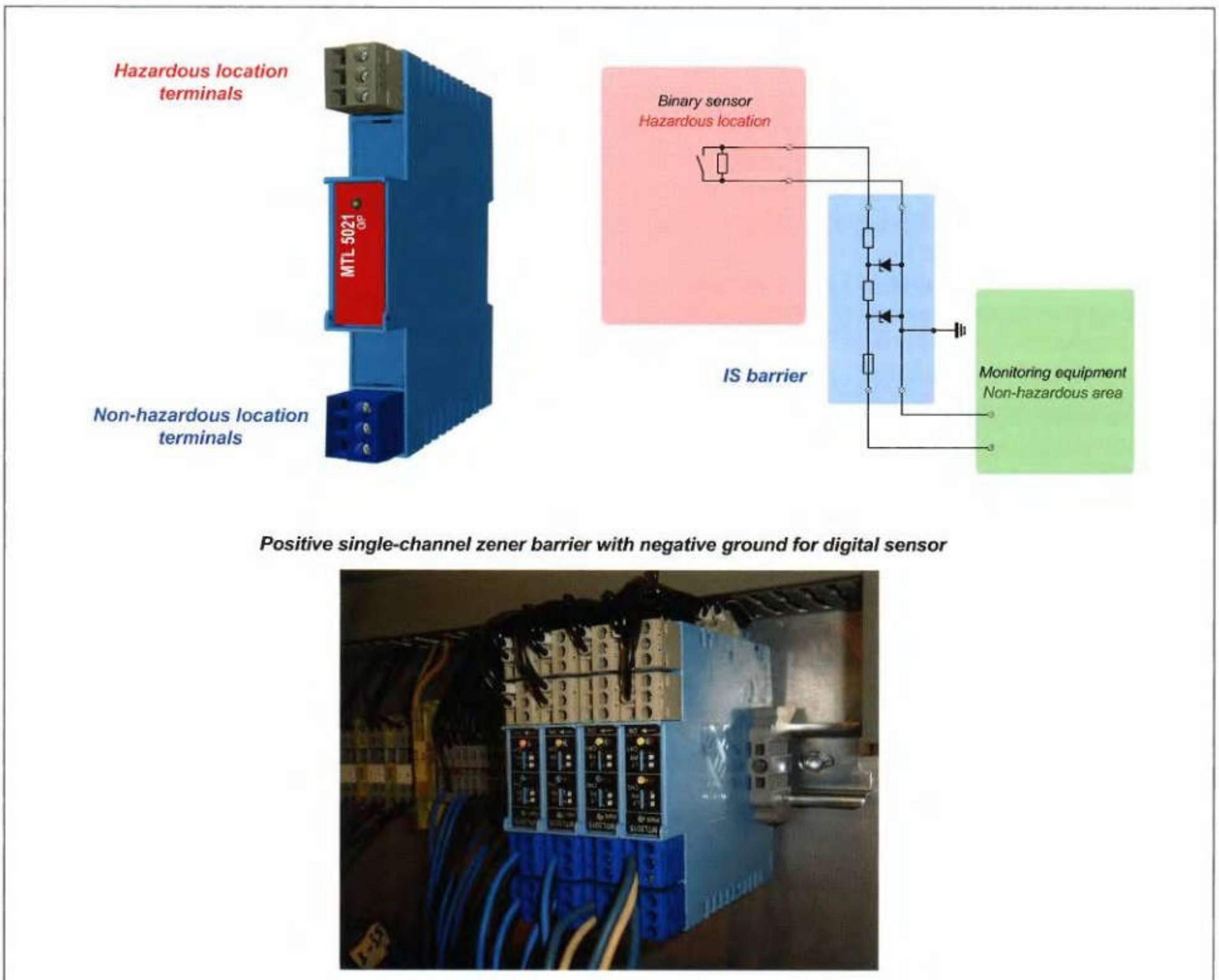


Figure 6.5 - Exi barrier construction

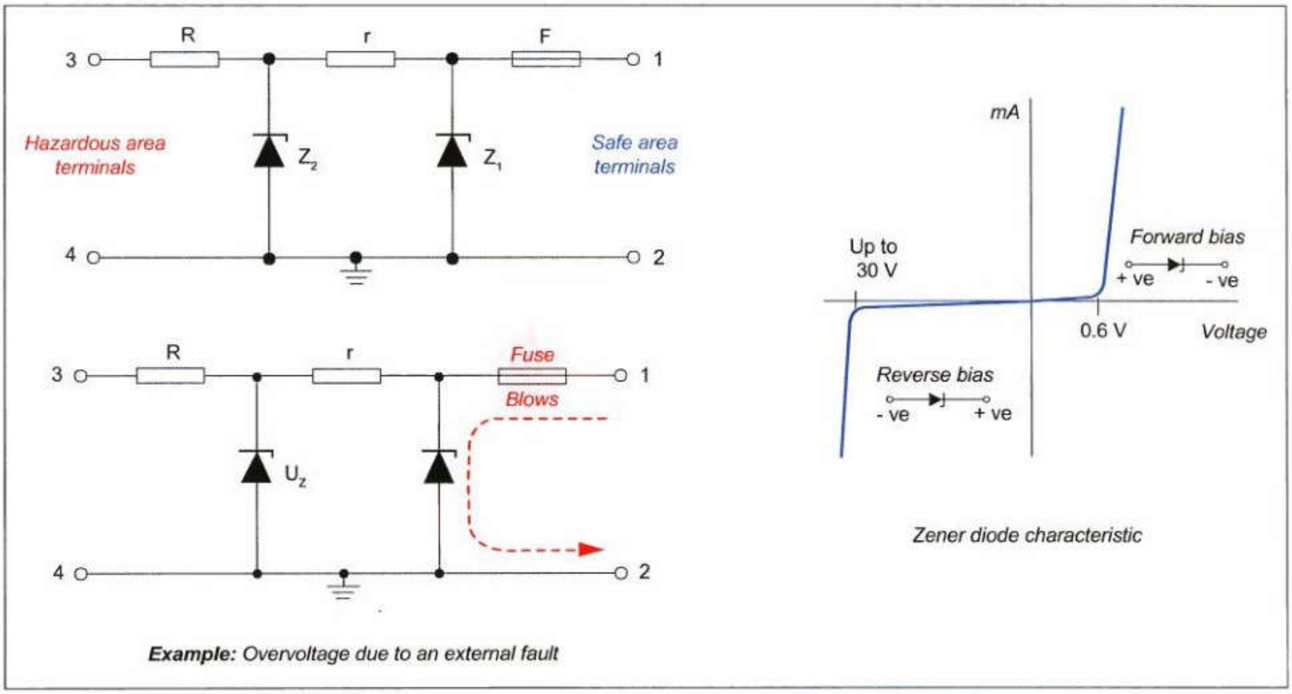


Figure 6.6 - Exi barrier operation

it, irrespective of the size of current flow. In normal operation, the instrumentation circuit has a supply voltage lower than the U_z voltage rating of the zener diodes so no current flows through them.

When an accidental high voltage appears at the input to the barrier, the diodes conduct to clamp their voltages to their U_z rating. This then limits the maximum voltage appearing on the hazardous area wiring. While the zeners are conducting, the current level is designed to blow the fuse that now isolates the circuit to maintain safety in the hazardous area.

In the event of a short-circuit on the hazardous area wiring or equipment, the in-line resistors within the barrier will limit the size of fault current while the fuse blows. Two or three zener resistor combinations are used within a barrier to provide backup voltage anchors while the fuse is blowing.

After clearing a fault, the complete zener barrier must be replaced with an identical unit. No alterations to the original are allowed as this is a certified Ex safety device.

Cables for intrinsically safe circuits on board ships should be separated from power cables and the crossing over of such cables should be at 90°. This is to minimise electromagnetic interference from the power cables affecting the intrinsically safe circuits.

The metallic cable screens of intrinsically safe circuits should be earthed, at the power supply end only, to prevent circulating currents within the sheath.

Power and intrinsically safe cable runs should be separately identified, ie by labels or by using cables with a distinctive colour (typically blue for Exi).

6.7 Exe Increased Safety

Equipment designated as Exe is based on the containment of open sparking at locations such as relay, switch contacts, the commutators or slip rings of motors and generators, and on the close control of surface temperatures.

In addition, the construction of the equipment is to a very high standard to prevent faults developing. Extra insulation is used, creepage distances between bare terminals are made longer and special enclosures to protect against damage due to entry of moisture and mechanical damage are also specified (see Figure 6.7).

The enclosure is made to withstand impact and to prevent ingress of solids and liquids. Applications include cage-rotor induction motors, luminaires and connection boxes. Special Exe cable glands, metal or plastic, are used with Exe apparatus.

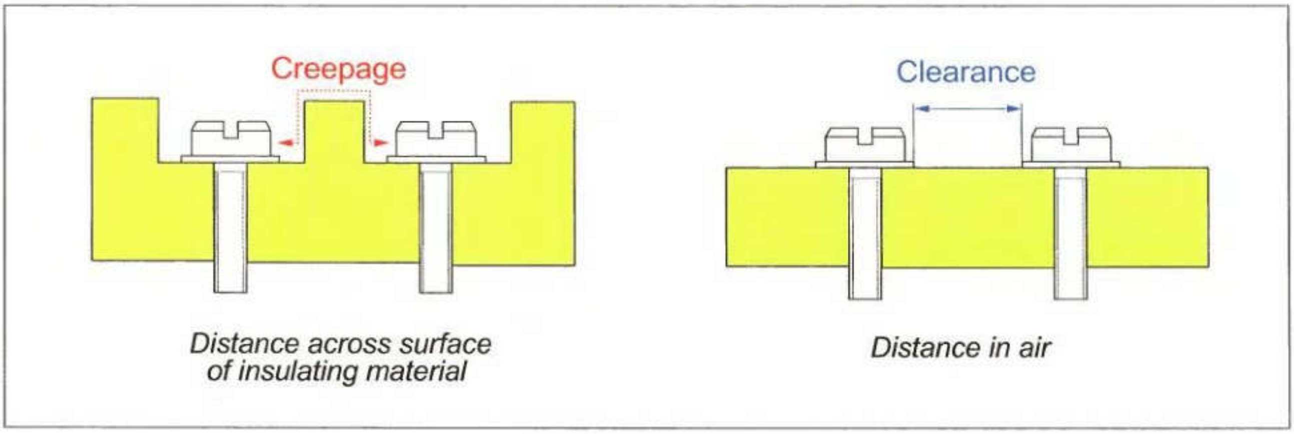


Figure 6.7 - Creepage and clearance distances

6.8 Exn Non-Sparking

Similar to Exe, the designation Exn applies to equipment that has no arcing contacts or hot surfaces that could cause ignition.

The Exn requirements are less stringent than for Exe, and designs are very close to that of normal electrical apparatus.

The main consideration is extra care to ensure locking of terminal connections to avoid any risk of electric sparking or flashover.

6.9 Exp Pressurised Apparatus

Clean, dry air or an inert gas is supplied to the equipment slightly above atmospheric pressure to prevent entry of the external flammable gas. This method is sometimes used for motors, instrumentation enclosures and lighting.

The diagrams in Figure 6.8 show that the internal pressure may be maintained by leakage compensation or by continuous circulation. A pressurisation system requires a purge flow before the internal electrical equipment is permitted to operate. The pressurised enclosure must also be fitted with alarm and trip signalling for a reduction of pressure which, in turn, will switch off the enclosed electrical circuits.

6.10 Exm Encapsulation

This works by enclosing the equipment in organic resins to keep the potentially explosive atmosphere away from the source of ignition. The encapsulation provides protection from increased temperature under normal and fault conditions.

6.11 Installing and Operating Electrical Systems in Hazardous Areas

The relative regulations are specified in EN 60079-14.

Cable systems are mainly used in Europe for electrical installations. For this, high quality cables are laid unprotected. It is only in areas in which mechanical damage could be expected that they are laid in conduits that are open at both ends.

Three installation systems are used for electrical systems in hazardous areas:

Cable system with indirect cable input
In the case of indirect entry, the cables and lines are conducted via cable glands into a connection chamber in the type of protection 'increased safety' and connected to the terminals also provided in 'increased safety'. From here, the individual wires are conducted via flameproof bushings into the flameproof enclosure. The cable bushings are installed by the manufacturer, with the result that, by contrast with direct entry, a routine test of the factory-wired flameproof enclosure can be made. The terminals also have the protection type 'increased safety'.

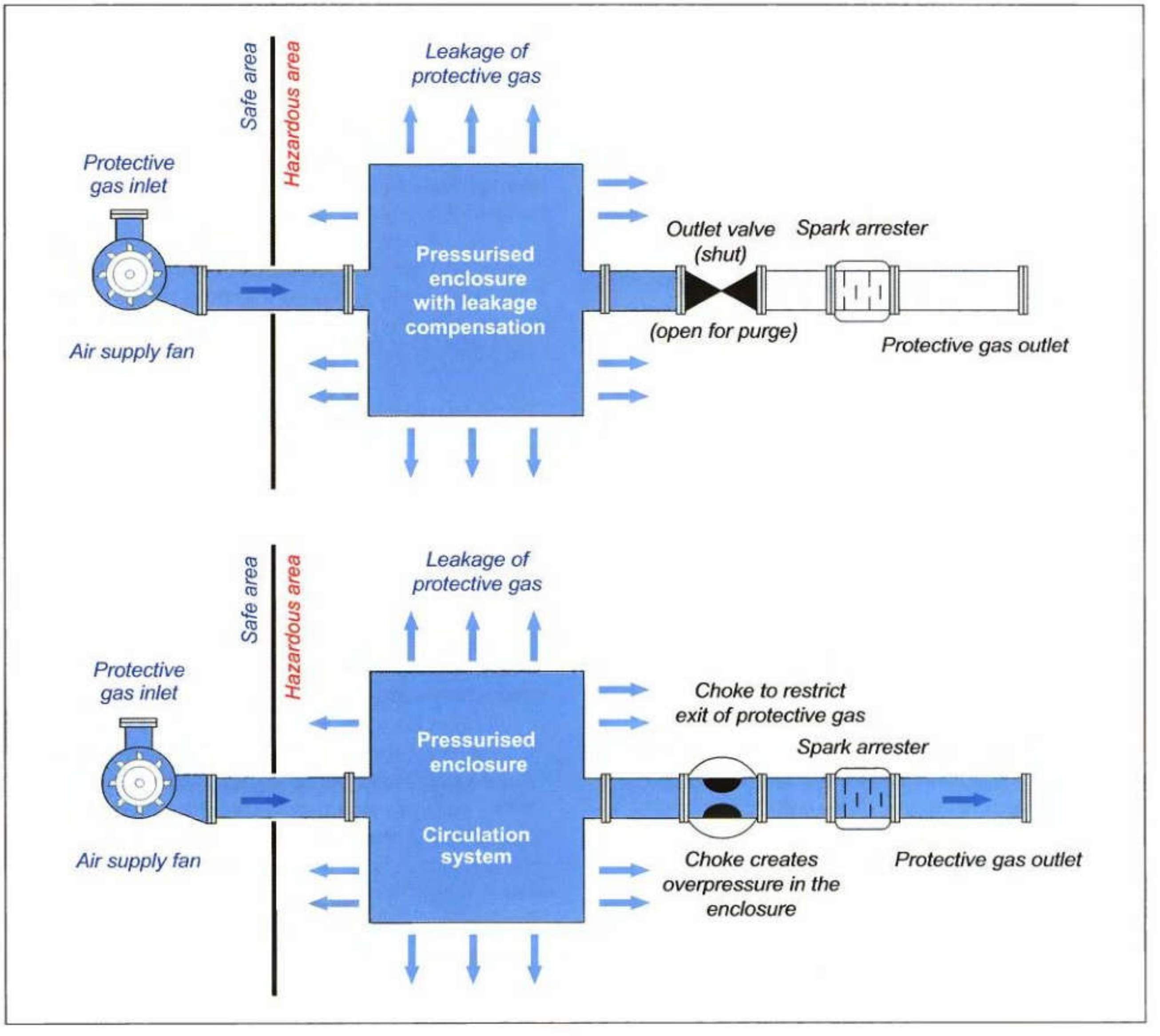


Figure 6.8 - Exp (pressurised) enclosure arrangements

Cable system with direct cable input
The cables are run direct into the device installation areas. Only cable glands specially certified for this purpose can be used.

Conduit systems
The electrical cables are fed into the closed metal piping as single cores. The piping is connected to the housing using glands and is provided with a seal at every inlet point. The entire piping system is flameproof in design. The piping system is also known as a conduit system.

Regular servicing is required to maintain the safety of electrical systems in hazardous areas. Some of the most important safety measures are:

- Carrying out work on live electrical systems and equipment is prohibited in hazardous areas. Work on intrinsically safe circuits is a permissible exception
- in hazardous areas, grounding or short-circuiting is only permissible if there is no danger of explosion
- in the case of all work carried out in hazardous areas, there must be no possibility of ignitable sparks or excessively hot surfaces occurring that may cause an explosion if in conjunction with a potentially explosive atmosphere.

6.12 Additional Class Rules for Tankers

The Classification Society of a tanker carrying combustible gases and vapours will have a set of additional rules. It is important to ensure that the vessel remains within Class by giving these rules close review and consideration. The rules will cover aspects such as:

- Power supply systems
- cable installation
- electrical equipment in hazardous areas and extended hazardous areas
- motors
- measuring, signalling, control and intercommunication circuits
- fans and ventilation
- integrated cargo and ballast systems
- active cathodic protection systems.

6.13 Electrical Testing in Hazardous Areas

All electrical apparatus and associated circuits must be tested periodically in accordance with a defined testing routine with recorded test results.

Insulation resistance, earth loop resistance and earth continuity resistance tests must be made, the last two in relation to the setting or rating of the protective devices associated with the apparatus and its circuitry.

It is important that insulation resistance tests are NOT made in such a way that the safety devices and insulation used in intrinsically safe apparatus and circuits are damaged by excess test voltages.

No apparatus should be opened in a dangerous area until it has been made dead (no longer live) and effective measures (eg locking-off the isolating switch) have been taken to prevent its being made live again inadvertently.

Where, for the purpose of electrical testing, it is necessary to restore the power supply before the apparatus is reassembled, tests should be made using a suitable gas detector and continued during the operation to ensure that combustible gases do not approach the explosive limit.

Only if the hazardous area can be made gas free, or otherwise safe, or the electrical equipment is removed from the area, may insulation resistance testing be carried out, using a 500 V DC tester of certified intrinsically safe (Exi) design.

The testing and maintenance of flameproof or intrinsically safe equipment should be entrusted only to competent persons who have received instruction in the special techniques involved.

The body material of instruments and tools required for maintenance purposes should be designed so that they will not make a hot spark when dropped.

The energy output of all intrinsically safe instruments should be so small that they do not produce hot sparks. An insulation tester has a drooping characteristic to prevent high currents and may be intrinsically safe when applied to circuits of small inductance or capacitance, but a risk may arise when such energy storing properties of a circuit have an appreciable value.

Where such instruments are used, the test leads should be firmly connected throughout and, on completion of the test, they should not be detached until the circuit has been discharged through the testing instrument (leave the tester for one minute after the test is finished).

6.14 Maintenance of Exd-protected Apparatus

Figure 6.9 - Exd (flameproof) motor construction

The inspection and maintenance of Exd (flameproof) enclosures for luminaires, switches, junction boxes, push buttons, etc requires meticulous care.

The following example is a guide to the inspection and maintenance points as applied to a flameproof luminaire:

Corrosion

This will reduce the enclosure strength. To ascertain the extent of corrosion, remove dirt, loose paint and surface corrosion with a wire brush. If only the paintwork is deteriorating, the enclosure should be repainted to prevent further corrosion.

Bolts

Make sure that there are no missing bolts. This is particularly important on flameproof luminaires because a missing bolt will invalidate the certification. Replacement bolts must be of equivalent strength as originals (usually high tensile steel).

Mountings

Ensure all mountings are secure. Corrosion and vibration are severe on ships and can cause premature failure.

Flamepaths

Examine the flamepath for signs of corrosion or pitting. If the flamepath needs cleaning, this should be done with a non-metallic scraper and/or a suitable non-corrosive cleaning fluid.

Cement

Examine the cement used around lamp-glass assemblies both inside and outside. If the cement is eroded, softened or damaged in any way, advice should be sought from the manufacturer regarding repair. If deterioration of the cement has occurred, a complete new lamp-glass assembly should be fitted.

Lamp-glass

If cracked or broken, a complete, new lamp-glass assembly should be fitted. Clean the lamp-glass.

When re-assembling an Exd enclosure, you must ensure that:

- All flamepaths and threaded components are lightly greased with an approved form of non-setting silicone grease. Care must be taken to ensure that blind-tapped holes are free from accumulated dirt or excessive grease that can prevent the correct closure of flamepaths or cause damage to the tapped components. Fit a new lamp of the correct rating
- bolts are not over-tightened as this can distort flamepaths, cause excessive stress on lamp-glasses or distort weather-proofing gaskets, if fitted, allowing the ingress of liquids and dusts
- the luminaire is installed in accordance with the requirements of the installation, particularly the classification of the area if it is hazardous, and that the correct rating of lamp is fitted
- any build-up of dust on the luminaire is removed as it can cause overheating and act as a corrosive agent.

Before attempting any maintenance work on Exd equipment, check for any particular inspection and overhaul instructions given by the manufacturer.

Chapter Seven
Periodic Survey Requirements

The following periodic surveys are carried out on merchant vessels:

- Annual
- Intermediate
- Class renewal survey.

Annual surveys are conducted for the hull and the machinery, including the electrical plant and, where applicable, for special equipment.

Extended annual surveys, referred to as intermediate surveys, fall due approximately 2.5 years after commissioning, at each class renewal and may, for seagoing ships, also be carried out at the second or third annual survey.

Class renewal surveys are carried out for the ship's hull and machinery, including the electrical plant. Any special equipment will be surveyed at the intervals indicated by the Classification of the hull.

The electrical equipment on board will be subject to mandatory periodic type approval as prescribed under the regulations for the Classification of the ship.

7.1 SOLAS

SOLAS contains electrical regulations within Chapter II-1 *'Construction Structure, subdivision and stability, machinery and electrical*, which is divided into five parts:

✧	Part A	General
✧	Part B	Sub-division and stability
✧	Part C	Machinery installations
✧	Part D	Electrical installations
✧	Part E	Additional requirements for periodically unattended machinery spaces.

Electrical installations (Part D) is sub-divided into:

✧	Regulation 40	General
✧	Regulation 41	Main source of electrical power and lighting systems
✧	Regulation 42	Emergency source of electrical power in passenger ships
✧	Regulation 42-1	Supplementary emergency lighting for ro-ro passenger ships
✧	Regulation 43	Emergency source of electrical power in cargo ships
✧	Regulation 44	Starting arrangements for emergency generator sets
✧	Regulation 45	Precautions against shock, fire and other hazards of electrical origin.

7.2 Classification Societies

Classification Societies verify the strength, function, reliability and integrity of essential parts of the ship including the propulsion, power generation and auxiliary systems.

The *International Association of Classification Societies* (IACS) is a technical organisation that provides a forum for 13 major Classification Societies (Class) to discuss, research and adopt standards for maritime safety.

Electrical equipment and services on board ship must also meet the minimum standards specified by various national and international organisations.

The standards specified by organisations are met when the ship is designed, built, approved and classified by the classification society.

The shipowner and operating staff must maintain the vessel and its electrical installation to the requirements of the Classification Society throughout the ship's lifetime.

7.3 Main Electrical Survey Items

The following survey items generally apply to all ships:

- Generators and governors
- circuit breakers
- switchboards and fittings
- cables
- insulation resistance
- motors and starters
- emergency power equipment
- parts of steering gear
- navigation light indicators.

For unattended machinery space (UMS) operation, a survey of the associated alarms, controls and fire detection is also required.

For tankers/gas carriers and other ships transporting flammable cargo, an additional survey of all electrical equipment in hazardous areas is carried out during each docking survey and annual survey.

7.4 Generators and Governors

The surveyor will require that main and emergency generators are clean, respond correctly to controls and load changes and show stable operation when required to run in parallel with other generators.

Generator windings on the stator and rotor must be free of dust, oil and moisture (see Figure 7.1). A visual check will be made for any obvious deterioration, abrasion or cracking of the insulation around the end winding coils on the stator.

An insulation test to earth and between stator phase windings (if the neutral point can be disconnected at the terminal box) should be carried out while the machine is still hot after running on load (see Figure 7.2).

The rotor circuits must also be tested for insulation value, taking care to short out the rotating shaft diodes of a brushless excitation system as the diodes usually have a low peak inverse voltage (PIV) rating.

QUESTION

Would an IR test result of 0.5 MΩ to earth be acceptable for a 440 V main generator?

ANSWER

Although a minimum of 1.5 MΩ is generally specified for new equipment, 0.1 MΩ should be acceptable in special cases. However, most surveyors would insist on at least 1 kΩ/volt, ie 440 kΩ, say, 0.5 MΩ as a reasonable minimum value for a 440 V generator. For HV equipment, the usual recommended minimum IR level is (kV + 1) MΩ, eg for a 6.6 kV motor, the acceptable minimum IR would be 7.6 MΩ.

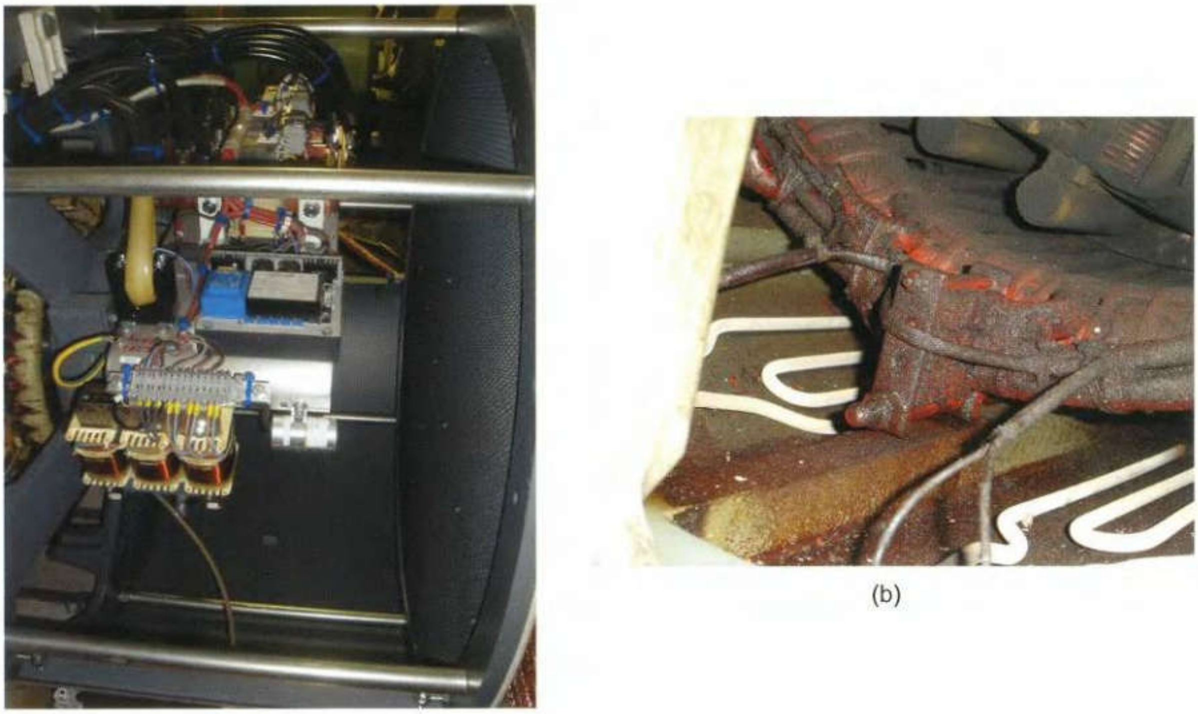
Remember to disconnect all AVR equipment, instrument connections and generator heater supplies when testing for IR.

Special attention to the contact surface of any commutator or slip rings is required. The contact surfaces must be smooth and concentric without any signs of pitting or deep grooves. Carbon brushes must be of adequate length, maintained at the correct spring pressure and properly contoured onto its rotating commutator or slip ring. Be sure to remove any excess carbon dust in the vicinity of the brush gear and around rotor coils.

Generator running tests, on load, should confirm the proper operation of governor and AVR controls with correct voltage, frequency and current values indicated on the generator control panel. Governor droop and its response to sudden load changes must be within the declared specification for the prime mover/generator combination. Stability of load sharing of kW and kVAr (or load current/power factor) between two or more generators running in parallel, as well as the reverse power trip of each generator's circuit breaker, must be demonstrated.

Automatic start functioning and switching under load of the standby generator in the event of blackout must be shown in action for all generator sets.

It is regular practice to carry out all the tests related to the electrical installations on board prior to the surveyor's visit. This will ensure their correct operation and allows time to resolve any problems that may occur.



(a) (b)

Figure 7.1 - Generator's excitation system component condition
a) SE generator excitation components (clean and oil free)
b) CAT generator view at the stator winding and space heaters (unacceptable condition due to covering of oil and dust)

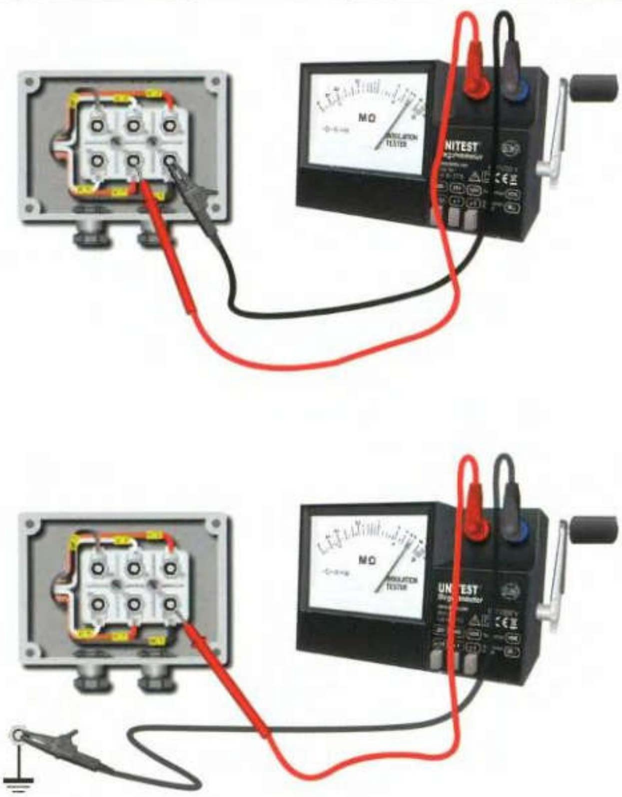


Figure 7.2 - Induction motor's insulation resistance (IR) test

7.5 Circuit Breakers

A visual examination of circuit breakers in main, emergency and section boards will usually precede operational tests. The surveyor will also check for overload current and short-circuit protection settings. Main terminals at the rear of the ACB should be inspected for signs of overheating.

Arc chutes must be clean, free of debris and correctly aligned. All internal wiring should be in good condition and the end connections must be tight. The surveyor may request that all mechanical linkages are checked for any signs of wear or stress.

Figure 7.3 - Generator's ACB

While checking the generator's circuit breaker, the surveyor may ask to see its closing and trip operations while in its isolated position (ie not connected in circuit). The racking mechanism for moving the breaker from the service to the isolated position must be demonstrated to be free moving and the fixed main terminals must be seen to be shuttered off when the breaker is withdrawn. Emergency hand charging (if fitted) of the closing spring will be tested. Correct operation of the mechanical indicators to show whether the breaker is open, closed or isolated is required.

These test procedures are generally related to surveys carried out for newbuild vessels. They are rarely carried out for annual, intermediate and Class surveys. However, it is for the surveyor to decide which particular operations he will test.

Similar test procedures should be scheduled during the regular checks carried out by the engine crew.

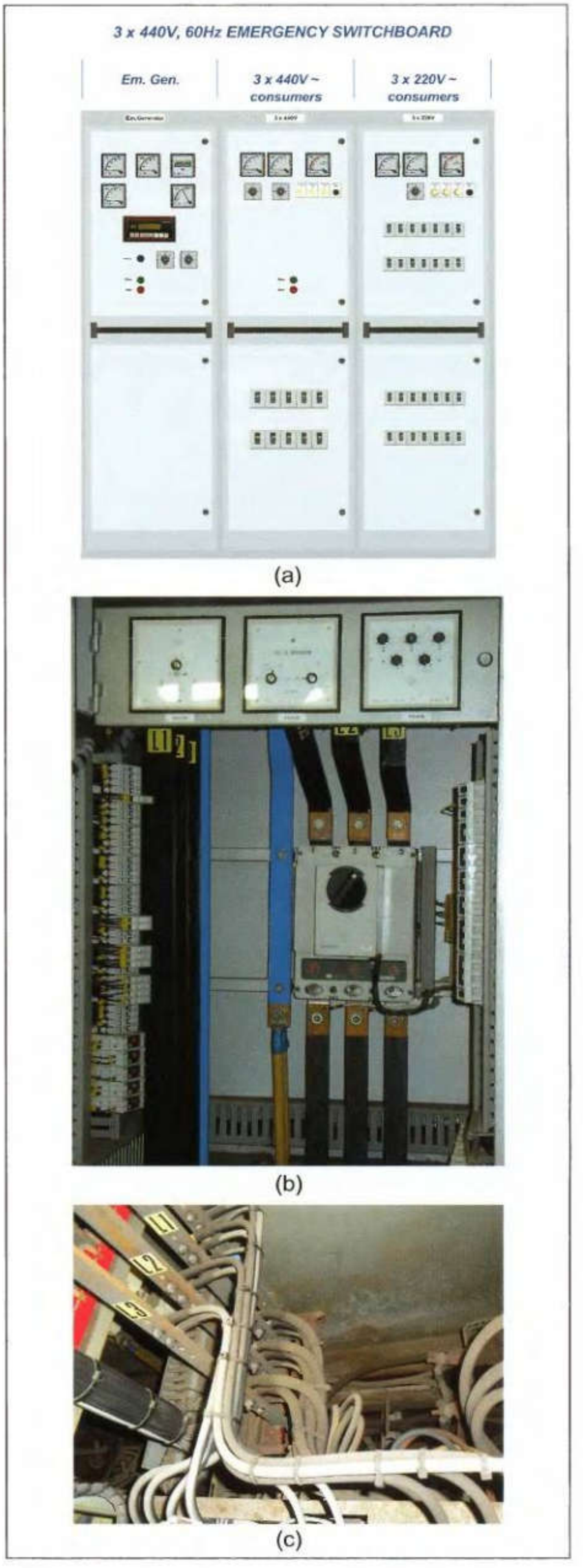


Figure 7.4 - Emergency switchboard
a) Panel arrangements
b) Internal view at ESB panel's components
c) Busbars and main connections' condition (unacceptable due to accumulated dirt on all internal components)

The undervoltage release mechanism and overcurrent trip settings for level and time delay may have to be demonstrated to the surveyor's satisfaction. An overcurrent trip for a generator breaker is typically set for 130% of FLC, with a typical time delay of 3 seconds, but this has to suit the thermal capacity of the generator and be coordinated with the overall protection scheme for the power system.

Although the overcurrent and time delay settings on the breaker can be seen to be correctly adjusted to the desired values, only a proper current injection test will prove these settings against the manufacturer's I/t characteristics. In this test, the circuit breaker is isolated from the busbar and a set of calibrated currents from a current injection set are fed directly through the closed circuit breaker (primary injection) or (more usually) through the overcurrent relay (secondary injection). This is generally a specialist task for an outside contractor.

7.6 Switchboards and Fittings

One of the main survey requirements for any switchboard, section board or distribution board is that they are clean. This includes all internal surfaces as well as the external panel surfaces, instrument faces and control switches. A thorough cleaning job on the inside of the main switchboard can only be safely carried out when the board is completely dead (all generators stopped and prime movers locked off).

All the main busbar and auxiliary connections throughout the boards should be checked for tightness during the dead period of a major internal clean up. Overheating signs at a connection junction are probably due to a loose joint. Direct heat testing on load with an infrared thermal camera is a useful technique for locating hot-spots.

Busbar supports will be examined for surface tracking and damage to the insulation material. All internal wiring within the switchboard panels must be securely fixed. Cable entries at the bottom of the switchboard should be sealed with a non-flammable material to exclude dirt and act as a fire stop.

The main switchboard earth bar must be securely bonded to both the frame of the board and the ship's hull. One secondary terminal of each current transformer (CT), and the metal cases of instruments and relays, should be wired to the main earth bar. Hinged panel doors should be bonded with an earth strap to the main switchboard frame.

QUESTION

What is the reason for earthing one end of the secondary winding of a CT?

ANSWER

If insulation between primary and secondary windings breaks down, the secondary circuit can be raised to full primary voltage, eg 440 V above earth, which could damage the secondary insulation and create a serious risk to personnel. By earthing one end of the CT, the circuit is anchored to zero volts. In addition, the earth connection will allow such a fault to be detected on the earth fault monitor.

Feeder isolator and fuse holder contacts must be checked for any mechanical wear or damage due to overheating or arcing at the contacts. A slight smear of a proprietary electrical contact lubricant on moving contacts is usually recommended.

Operational tests on a main switchboard will focus on the synchronising controls and generator protection relays, such as reverse power and preferential load shedding trips. Typical reverse power trip settings may range between 5-15% of the generator power rating, with a time delay of 0.5-2.5 seconds for a diesel drive. Equivalent settings for a turbo generator may be 2-5% and 5 seconds.

Time delay settings must allow for the operating practice on the ship. For example, cargo winches and cranes may, at times, feed power back into the supply network. Under light load conditions, such regenerative feedback may cause a generator to trip on reverse power if its time delay was set too short.

7.7 Cables

Apart from an IR (megger) test on a main cable run, the survey of cables and their installation is largely based on a close visual examination. Inspect for any external damage of a cable's outer sheath and wire or basket-weave armouring (if fitted). The cable must be adequately supported along horizontal and vertical runs by suitable cable clips or ties.

Where cable runs along an open deck have expansion loops, these must be examined for abrasion and wear.

Where cables pass though fire check bulkheads, they must be correctly glanded or pass through stopper boxes that prevent the passage of fire between compartments.

Common shipboard cable insulations used include EPR (ethylene propylene rubber) or butyl rubber that is sheathed with either PCP (polychloroprene or CSP (chlorosulphonated polyethelene).

Where EPR/butyl cable terminations may be subjected to oil vapour, it is usual to tape or sleeve the cable ends to prevent deterioration of the insulation. Check that taping is secure.

QUESTION

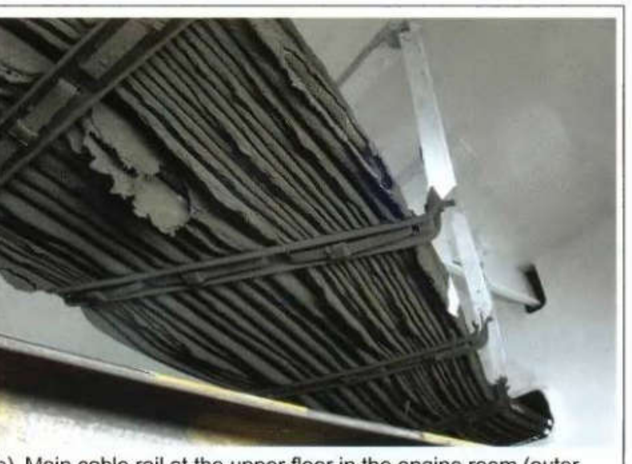
What are the functions of EPR or butyl and PCP or CSP?

ANSWER

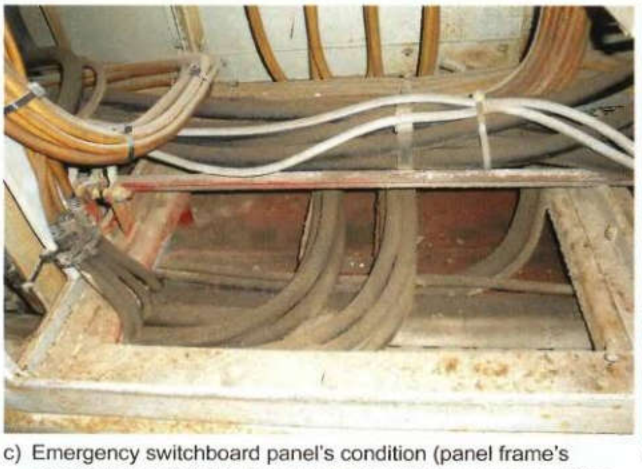
EPR or butyl rubber are good electrical insulators but are not mechanically strong or resistant to oil. This is why a sheath of PCP or CSP (which is stronger and has greater oil and fire resistance) is fitted around the inner insulation.

Flexible cables to light fittings, power tools, etc should be inspected for mechanical damage. In normal operation, a flexible cable may be repeatedly dragged and chafed, reducing its safety. If in doubt, replace flexible cables.

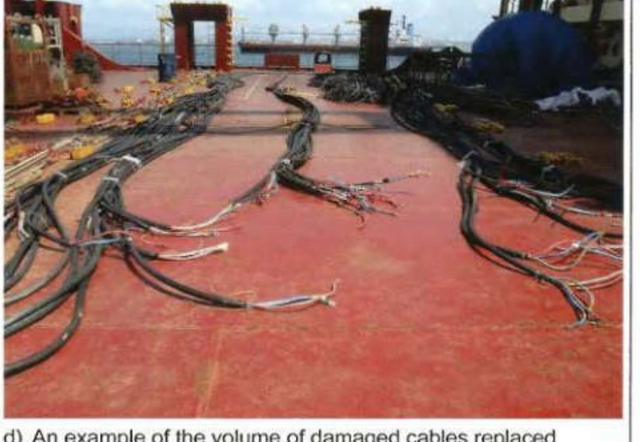
a) Crane power supply feeder's condition (cable rail has deteriorated to an unacceptable condition due to corrosion)



b) Main cable rail at the upper floor in the engine room (outer insulation sleeves have been damaged by overheating)



c) Emergency switchboard panel's condition (panel frame's condition has deteriorated due to extended corrosion; cables throughout the switchboard panels are heavily covered with dust)



d) An example of the volume of damaged cables replaced during a ship's repair

Figure 7.5 - Cable inspection

A copper strap or flexible earthing braid/wire is used to bond the steel frame of all electrical motors and other equipment to the ship's hull.

QUESTION

Why is such an earth bond required?

ANSWER

Without an earth strap, a loose internal wire may touch the frame, causing it to become live at mains voltage with consequent danger to operators. The earth strap electrically anchors the frame to the ship's hull (zero volts) to eliminate the shock hazard to personnel.

7.8 Insulation Resistance

The surveyor will require that an owner-approved megger test form be completed, which shows the results of recent insulation tests on all main 440 V and 220 V consumers.

The form should also indicate the test dates, weather conditions (hot, humid, etc) and any comments relevant to the test conditions (eg machine hot or cold).

An example of an IR log and its graphical trend for a motor is shown in Figure 1.10.

For essential items, such as generators and motors related to propulsion, mooring and cargo gears, the surveyor will be more interested in the IR trend, so a set of past results showing the insulation history of such machines may be requested.

7.9 Motors and Starters

After checking through the IR test results list, a surveyor may ask to witness a repeat test on selected motors. A visual examination of a motor frame and terminal box will reveal any damaged or missing parts. General neglect will be suspected if the motor is covered with dirt, oil or rust.

Totally enclosed, fan ventilated (TEFV) induction motors require little attention as their windings are protected against the external atmosphere. The surveyor will be more likely to concentrate on motors with drip-proof, weatherproof and deck watertight enclosures.

A running test on a motor will reveal any vibration problems, undue noise and worn out bearings. On load, the motor running current (shown on the ammeter at the starter) should be checked against the value indicated on the motor rating plate.

With starters and associated control gear, such as remote stop/start buttons, regulating resistors etc, an inspection will check for badly burned and misaligned contacts. The general condition of starter equipment will also be examined. This would include an inspection for loose connections, worn pigtails on moving contacts, badly carbonised arc chutes and signs of overheating on coils, transformers and resistors. Dust and weatherproof sealing features on a starter must be in place and in a serviceable condition.

Functional checks will test the normal operation of the starter from its local, remote and emergency control (if applicable) positions. Signal status lamps showing the motor/starter condition, eg running, off, tripped, etc, must be demonstrated as working correctly. Overcurrent trip settings should be compared with the motor FLC rating. Motor starter backup fuse size and type may be checked against the ship's/manufacturer's drawings and the motor rating.

7.10 Emergency Power and Associated Equipment

This section surveys the operation of the emergency generator and/or battery power equipment (inspection of the emergency generator itself is covered under the heading of Generators and Governors).

The emergency generator must be started, manually or automatically, while the initiation sequence and operation of starting equipment is observed.

Electrical supplies taken from the emergency switchboard should be checked to see if they are receiving their rated voltage, current and frequency when powered from the emergency generator.

Emergency lighting, fire pump and other emergency electrical equipment listed under SOLAS regulations must be functioning correctly. Electrical interlocking arrangements between the main and emergency switchboards must be checked. Auto-start initiation relays, whether voltage or frequency operated, will be examined and tested.

The ship's emergency battery installation, and its charging rectifier, will be examined. In particular, the battery environment must be dry and well ventilated. The battery tops must be clean with terminal posts and connections appearing free from corrosion. Figure 7.6 illustrates examples of unacceptable battery conditions caused by the failure to carry out regular maintenance. Image (a) shows the contaminated terminal connections of NiCd batteries used as emergency backup for various ship's services, and image (b) shows the burst casing of a lead-acid, maintenance-free battery set used for automatic backup power supply.

(a)

(b)

Figure 7.6 - Unacceptable battery conditions

Regular cleaning and greasing of all connections with acid-proof grease will protect batteries from being contaminated by aggressive sea humidity. Battery electrolyte should be at its proper level and have the correct value of specific gravity (SG), which should be checked with a hydrometer. Safety notices and personnel safety clothes (gloves, apron and goggles) should be available adjacent to the batteries. The ventilation arrangements for the battery locker will be checked.

Battery charging equipment should be checked for dirt, overheating, loose connections and correct functioning of indicators, instruments and alarms.

The surveyor may also require a battery maintenance list to be completed with the dates of battery replacements filled in.

7.11 Parts of Steering Gear

Figure 7.7 shows how an electrohydraulic steering gear system can be envisaged, from the surveyor's viewpoint, as being in three parts:

- Power unit
- steering control
- indications and alarms.

The power unit comprises duplicate electric motors and starters supplied from either side of the main switchboard. On many ships one of the steering gear motors will be supplied via the emergency switchboard, as recommended by the SOLAS requirements for vessel types such as passenger ships and ferries.

The motors, starters and any changeover supply switch units will be inspected under the same criteria outlined earlier in the section on motors and starters.

Rudder control from the bridge consoles, as well as emergency steering from the steering gear room, should be available. Main and alternative electric supplies, including any changeover facilities for the electric control from the steering wheel and for the auto pilot, must be tested.

The steering gear and its control must be functionally tested for its response. This is generally specified to be that the rudder must be swung from 32° port to 32° starboard in 28 seconds when driven by a single steering gear unit and it should take half that time when operating on both steering gears. A fully loaded response can only be obtained when the ship is loaded and under way at sea. Steering gear status indications must be operating correctly in the steering flat, main control room and on the bridge. The rudder position

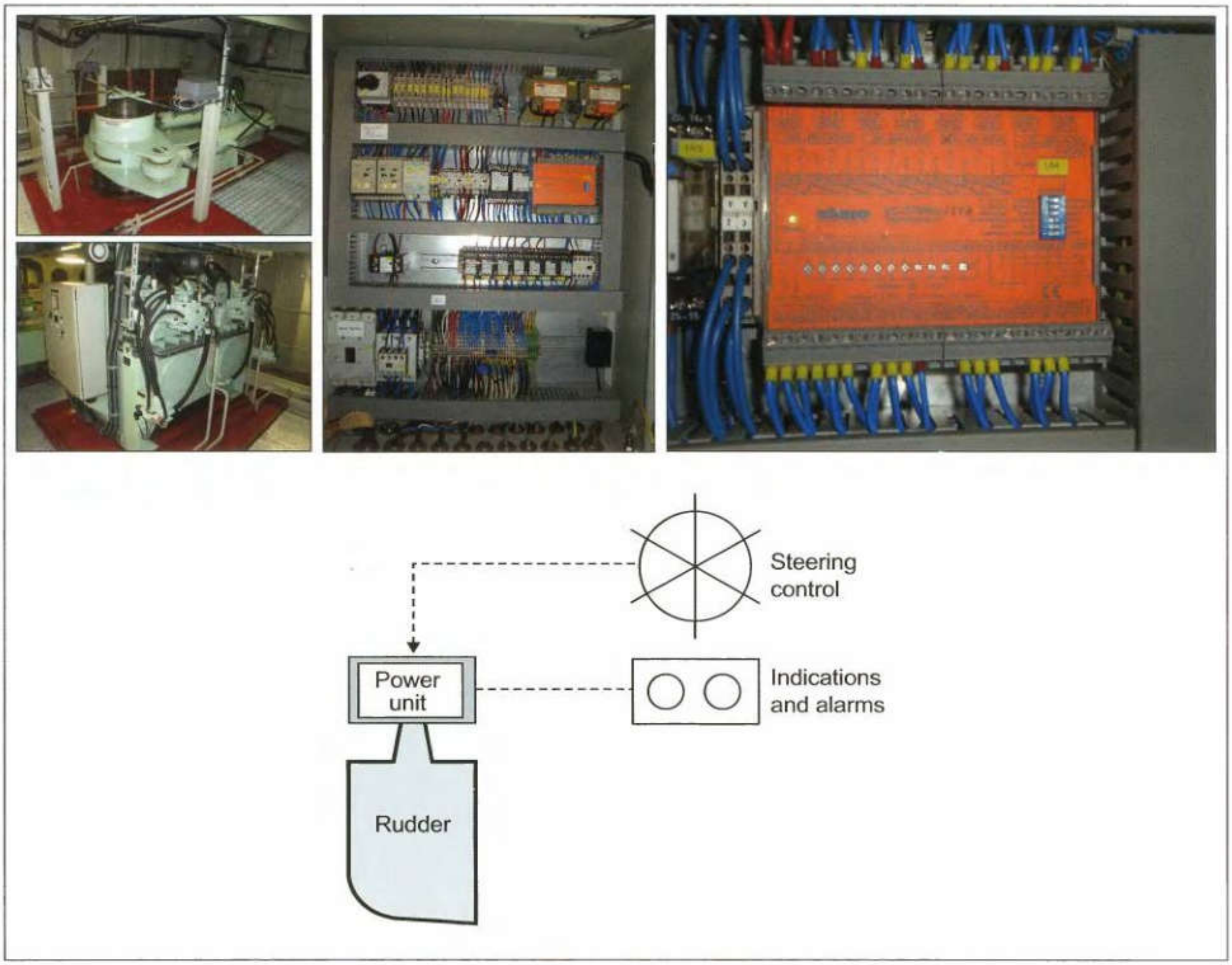


Figure 7.7 Main steering-gear components

indicators on the bridge may be checked during the functional testing of the steering gear. The bridge indication should be compared with the direct mechanical indicator on the rudder stock in the steering flat.

Motor overcurrent alarms can be initiated by simulating the action of the overcurrent relay. The phase failure alarm should be also tested by simulating the action of the voltage monitoring relay. Hydraulic fluid low level alarms must be checked for correct initiation by the oil level switch.

Remember that a steering gear motor does not have overcurrent trip protection; the only main circuit protection is from the backup fuses, which are essential for short-circuit protection.

7.12 Navigation Light Indicators

The surveyor will expect to prove that the navigation light monitoring system operates correctly and gives the appropriate alarms for a broken wire or burnt lamp. This can be achieved by removing an appropriate fuse.

The power supply for the navigation lights must be duplicated (usually the alternative supply is obtained from the emergency switchboard) and the changeover facilities must be checked (see Figure 7.8).

Although the actual light fittings for navigation are part of the safety equipment survey, the electrical survey will include a check on the supply cables to the lights.

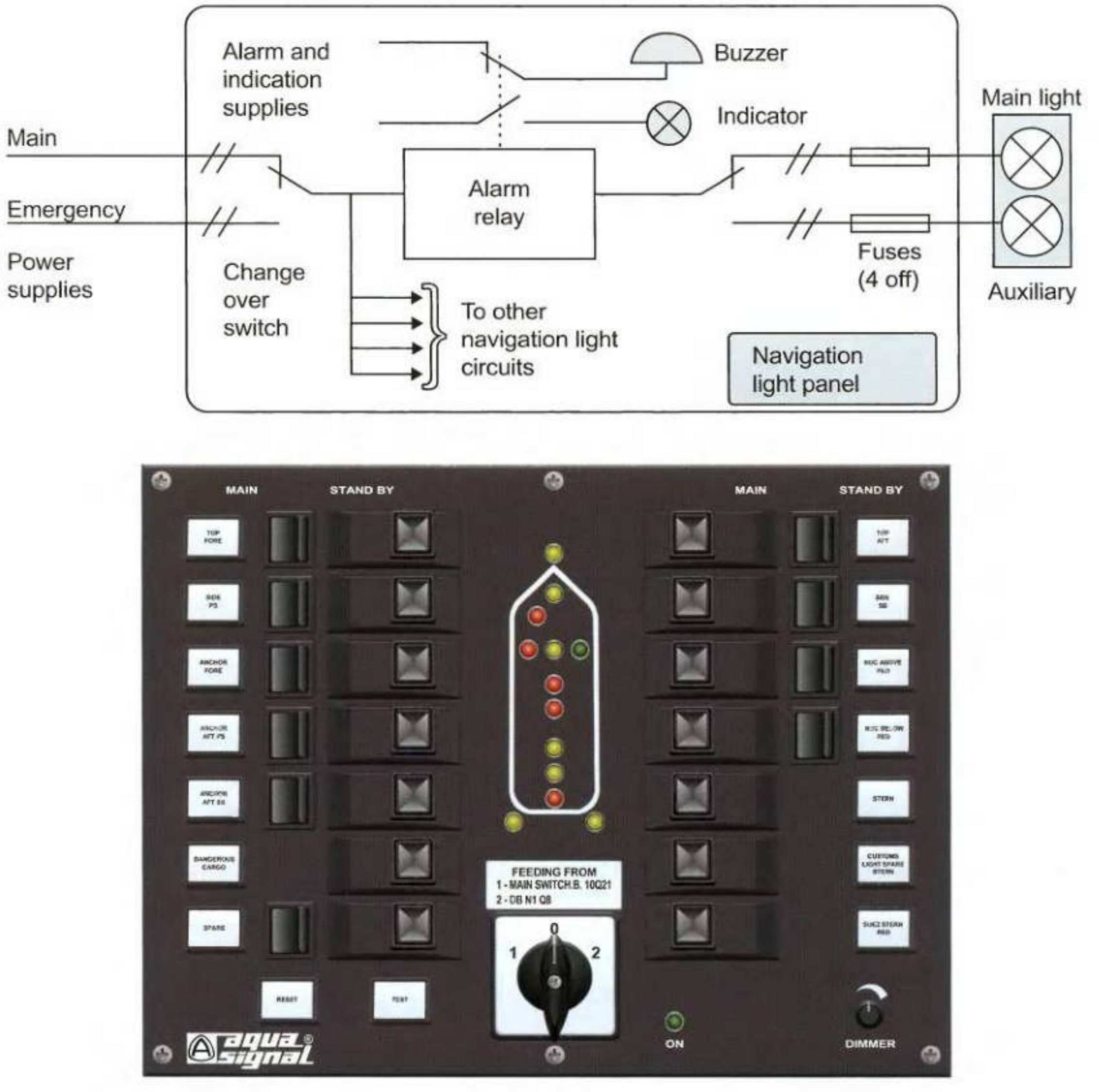


Figure 7.8 - Navigation light indicator panel

7.13 UMS Operation

If your ship is classified by automation Class for unattended machinery space (UMS) operation, the electrical survey will be extended to include all the alarms, fire detection, controls and failsafe features of such an installation.

All alarms associated with the propulsion, auxiliary engines and associated systems (eg lubrication and cooling) are to be tested for correct operation. Testing of the safety devices from the various systems is relatively straightforward. This can be achieved by either operating the relative sensor by hand or (more accurately) by simulating the action under the expected fault condition.

To prove that the overall sensor (pressurestat, thermostat, flow switch, level switch, etc) is functioning properly is more involved. Specialist contractors may be required to service and calibrate the process transducers, transmitters and alarm annunciators.

Attention will be paid to the propulsion and generator sets' related safety, particularly their alarms for lubrication and cooling systems. Initiation and action of automatic shutdown, slowdown or reduction features will be tested. Essential drives for lubrication, cooling and fuel supply are duplicated and arranged so that one pump can be selected on a duty/standby basis. Loss of pressure at the duty pump should automatically start up the standby unit.

UMS requirements demand that a standby main generator automatically starts and closes onto dead busbars on loss of the duty generator as quickly as possible. It is usual that the standby generator is started after a few seconds in the event of blackout.

This is followed by automatic sequential re-starting of essential auxiliaries for lubrication, cooling, fuel and steering. The correct functioning of the system will be tested.

Automatic startup and taking the load of the emergency consumers by the emergency generator must be demonstrated. The initiation of the automatic startup can usually be accomplished by disconnecting the transfer line (MSB-ESB) circuit breaker from either side. The emergency generator should then run up to the nominal speed and supply voltage to the emergency switchboard.

The main and standby electric power supplies to the overall alarm monitoring system must be inspected and tested.

The standby power arrangement usually includes battery backup. It will be necessary to inspect the general condition of the battery and its trickle charger.

Tests are made on the UMS alarm system to verify:

- That alarms displayed on the main console in the engine control room are relayed to the bridge alarm panel
- that the duty engineer call system is operating in the accommodation areas, ie in the cabin of the duty engineer and in the duty mess and lounges
- that the duty engineer is allowed 2-3 minutes to respond to a machinery alarm. If the engineer has not reached the control room and accepted the alarm within this time, a dead man alarm should be sounded, generally in the alleyway adjacent to the engineers' accommodation.

A complete inspection and test of the fire detection apparatus must be performed.

All smoke, heat and flame sensors must function correctly to initiate the appropriate audible and visual alarms on the bridge, in the main control room and in the accommodation. Hand-operated fire alarm switches (call points) of the 'break glass' type must also be examined and tested to be in proper working order.

Figure 7.9 - Break glass switch

The duplicate bilge level alarms, together with automatic bilge pumping (if applicable), must be proven to the surveyor's satisfaction.

Main engine controls and emergency stop buttons must function correctly and will be tested from the bridge and wings consoles, engine control room and at the emergency position alongside the engine.

The operational features of the electrical equipment for main engine control and indication will be best demonstrated during a full engine test during an engine survey. Electrical equipment and connections associated with engine control will be examined as usual for wear and tear, insulation level, cleanliness, loose connections and overheating.

7.14 Tankers

Electrical equipment in the hazardous areas of oil/gas carriers, and other ships carrying potentially dangerous cargo, will be surveyed during the periodic machinery surveys and during docking and annual surveys.

The most common form of hazardous area electrical equipment is the flameproof enclosure type (marked Exd on the equipment certification label). This type of enclosure will be found on light fittings, motors, starters, push buttons and alarm bells within the hazardous zones. (See Chapter 6.)

The flameproof enclosure will be inspected for surface cleanliness (which affects the surface temperature), corrosion and secure mountings. On lighting fittings, the cement that bonds the lamp glass to its frame must be closely inspected for

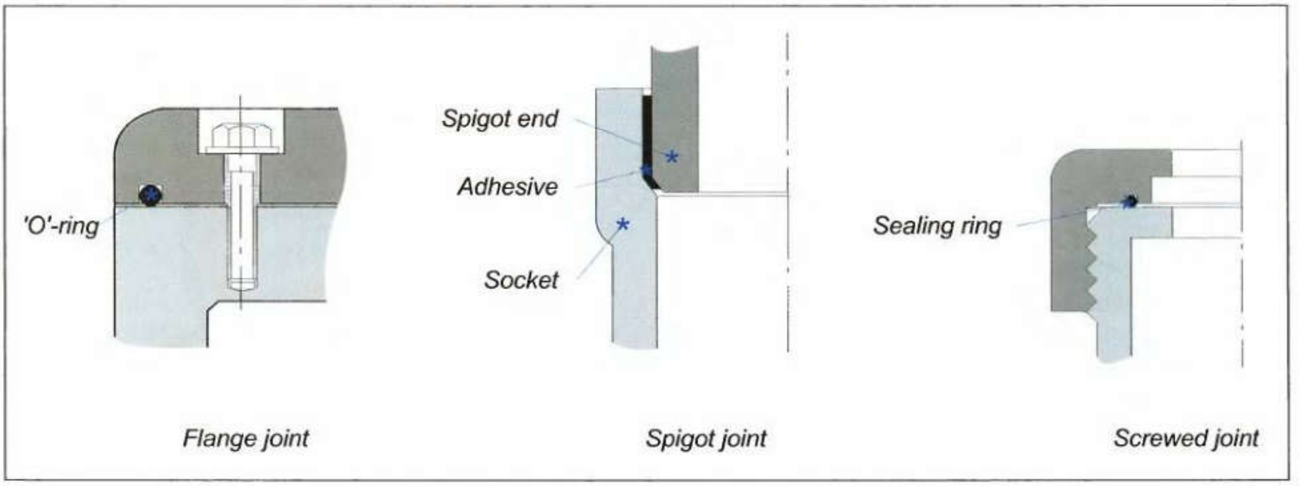


Figure 7.10 - Exd flamepaths

cracks or indentations. All bolts must be in place, evenly torqued-up and of the correct type.

The edges of flamepath flanged joints must not be painted over or impeded in any way. Exposed flameproof equipment on deck must be judged as weatherproof with the correct (approved) gaskets or 'O' rings in place.

An Exd fitting (Figure 7.10) may be opened up to check the condition of its flamepath surfaces for corrosion, pitting or scratch marks.

The Ex Certification label and equipment rating label must not be painted over.

Remember that no alterations to Exd equipment are allowed without permission from the Certification Authority.

Some pump rooms have pressurised light fittings (marked Exp on the Certification label). Here it is necessary to confirm that the fittings are purged and pressurised before the light is allowed to be switched on. Similarly, the lights should automatically be switched off if the air pressure drops below its set value.

Electrical instrumentation and communication equipment used in hazardous areas must be intrinsically safe (marked Exi on the Certification label). In most cases, zener barriers, as shown in Figure 7.11, are connected in line with intrinsically safe circuits and are fitted in a safe area just outside the hazardous area.

The surveyor cannot easily test zener barriers in situ as this would involve special equipment and it is generally accepted that such protection equipment will function correctly when circuit fault conditions arise. This is no different to accepting that a fuse will blow when a short-circuit occurs.

However, the surveyor will visually inspect the zener barrier installation. The barriers must have secure connections and be properly bolted to an earth strap which, in turn, must be solidly bonded to the ship's hull.

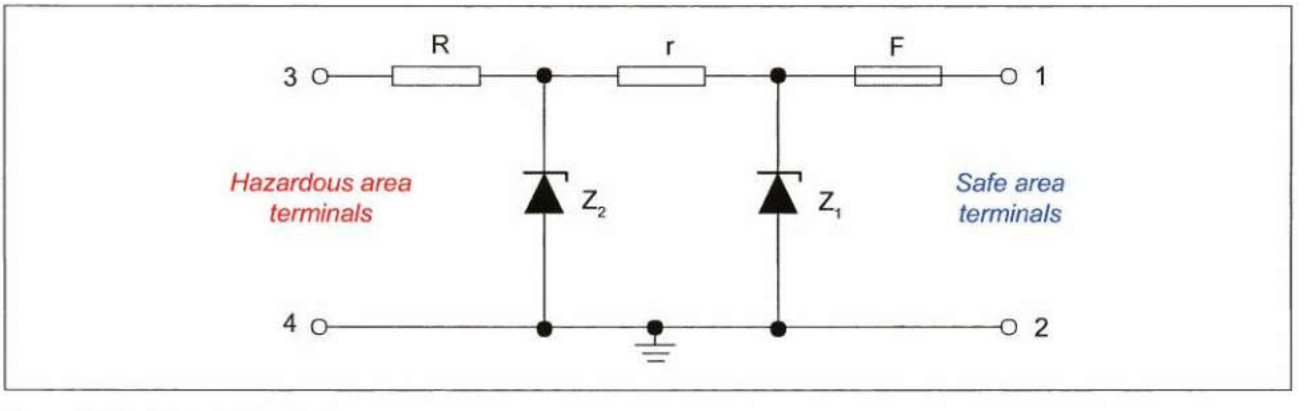


Figure 7.11 - Exi barrier circuit

Chapter Eight
Electric Propulsion and High Voltage

8.1 Electric Propulsion Scheme

Electric propulsion of ships has a long but somewhat chequered history. There have been periods when it has enjoyed popularity, with a significant number of installations being undertaken, while at other times it has been virtually ignored as a drive system.

Passenger ships have always been the largest commercial vessels with electric propulsion systems, but a wide variety of vessels have been, and are, built with electric propulsion.

Early large passenger vessels employed the turboelectric system, which involved the use of variable speed, and therefore variable frequency, turbo-generator sets for the supply of electric power to the propulsion motors, directly coupled to the propeller shafts. The generator/motor system acted as a speed reducing transmission system. Electric power for auxiliary ship services required the use of separate constant frequency generator sets.

A system that has generating sets that can be used to provide power to both the propulsion system and ship services has clear advantages, but this would have to be a fixed voltage and frequency system to satisfy the requirements of the ship service loads. The provision of high power variable speed drives from a fixed voltage and frequency supply has always presented problems. In addition, when the required propulsion power was beyond the capacity of a single DC motor, there was the complication of multiple motors per shaft.

There are reasons why, for some installations, it is possible to justify the complication of electric propulsion and these include:

- Flexibility of layout
- load diversity between ship service load and propulsion
- economical part-load running
- ease of control
- low noise and vibration characteristics.

Flexibility of layout

An advantage of an electric transmission is that the prime movers, and their generators, are not constrained to have any particular relationship with

Figure 8.1 - Modern cruise ship

the load as a cable run is a versatile transmission medium. In a ship propulsion system, it is possible to mount the diesel engines, gas turbines, etc in locations best suited for them and their associated services, so they can be remote from the propeller shaft. An example of an electric propulsion plant layout is shown in Figure 8.2.

Load diversity

Certain types of vessels have a requirement for substantial amounts of electric power for ship services when the demands of the propulsion system are low. Tankers are one instance of this situation and any vessel with a substantial cargo discharging load also qualifies. Passenger vessels have a substantial electrical load which, although relatively constant, does involve a significant size of generator plant.

Economical part-load running

This is best achieved when there is a central power generation system feeding propulsion and ship services, with passenger vessels being a good example.

It is likely that a typical installation would have between four and eight diesel generator sets and, with parallel operation of all the sets, it becomes very easy to match the available generating capacity to the load demand. In a four engine installation, for example, increasing the number of sets in operation from two that are fully loaded to three partially loaded will result in the three sets operating at a 67% load factor, which is not an ideal operating condition. It is not necessary to operate generating sets at part-load to provide the spare capacity to be able to cater for the sudden loss of a set, because propulsion load reduction may be available instantaneously and, for most vessels, a short time reduction in propulsion power does not constitute a hazard.

The propulsion regulator will continuously monitor the present generator capability and any generator overload will immediately result in controlled power limitation to the propulsion motors. During manoeuvring, propulsion power requirements are below system capacity and failure of one generator is not likely to present a hazardous situation.

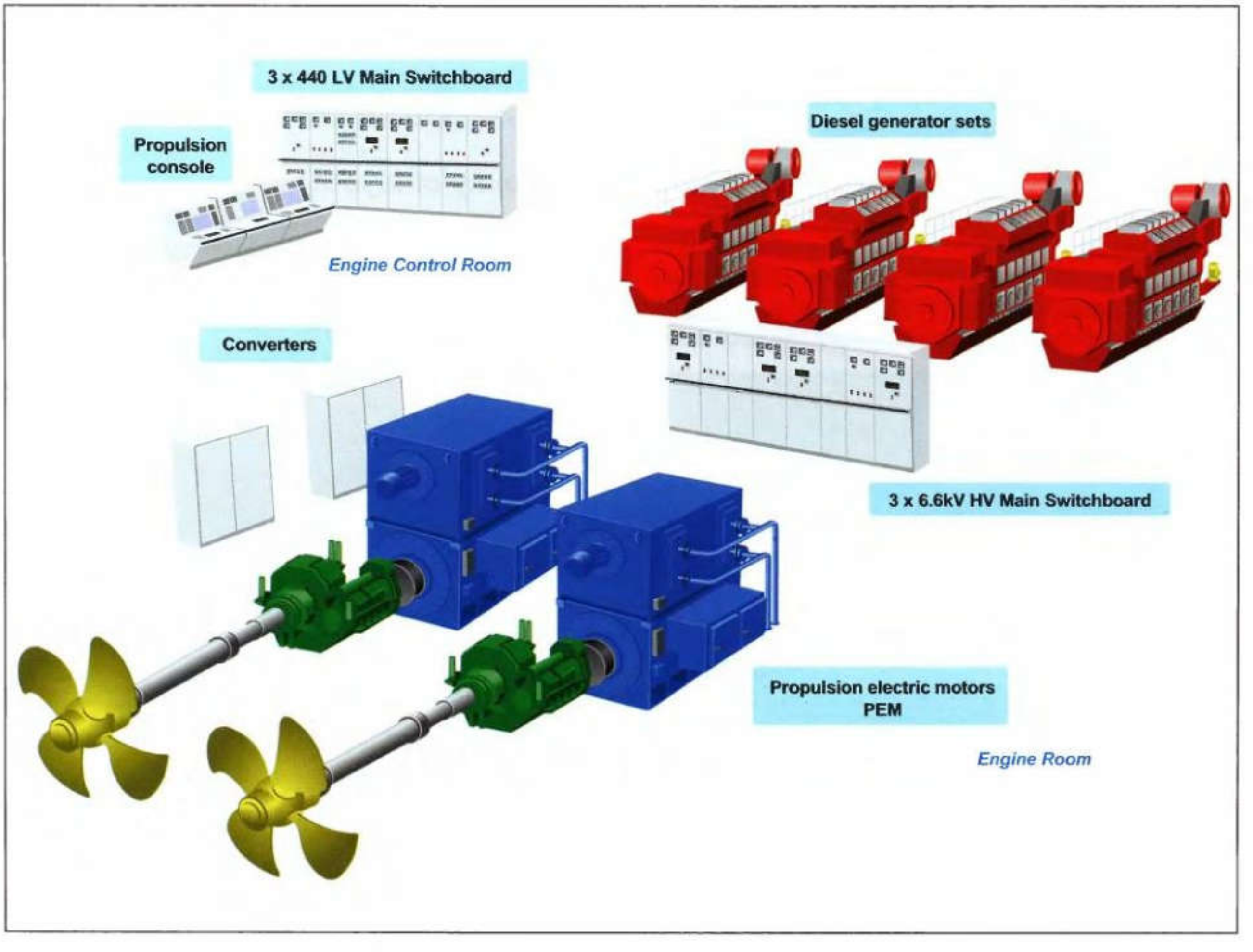


Figure 8.2 - Propulsion plant layout

Ease of control

The widespread use of controllable pitch propellers (CPP) has meant that the control facilities that were so readily available with electric drives are no longer able to command the same premium. Electric drives are capable of the most exacting demands with regard to dynamic performance which, in general, exceed by a wide margin anything that is required of a ship propulsion system.

Low noise

An electric motor is able to provide a drive with very low vibration characteristics and this is of importance in warships, oceanographic survey vessels and cruise ships. With warships and survey vessels, it is noise into the water that is the critical factor, while with cruise ships, it is structure-borne noise and vibration to the passenger spaces that has to be minimised.

An overview of practical electric drive options is shown in Figure 8.3.

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

The prime movers are conventionally constant-speed diesel engines driving AC generators to give a fixed output frequency. Gas turbine driven prime movers for the generators are likely to become more common 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 fitted within rotating pods mounted outside of the ship's hull. These are generally referred to as azipods, as shown in Figure 8.4, as the whole pod unit can be rotated through 360° to apply the thrust in any horizontal direction, ie in azimuth. This means that a conventional steering plate and stern side thrusters are not required.

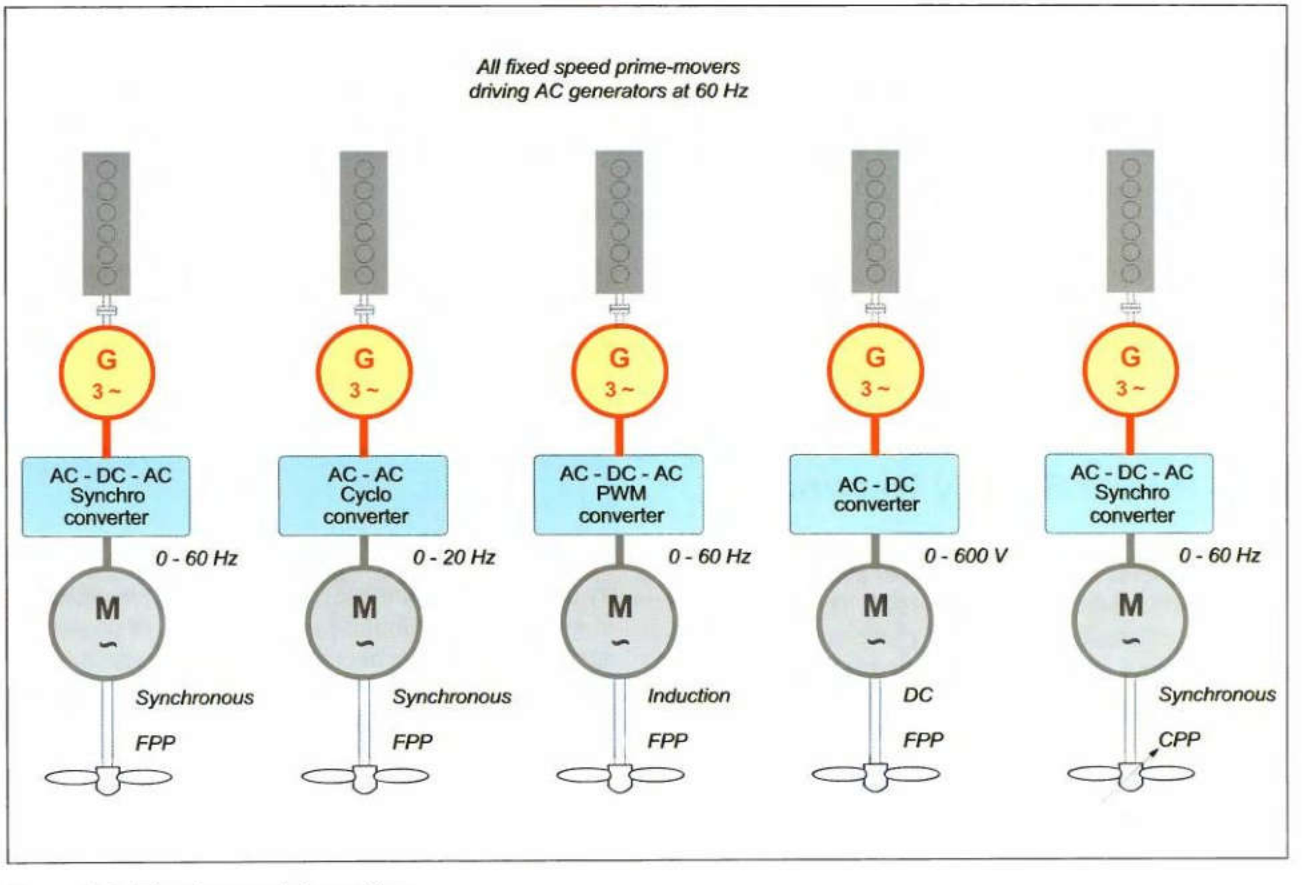


Figure 8.3 - Electric propulsion options

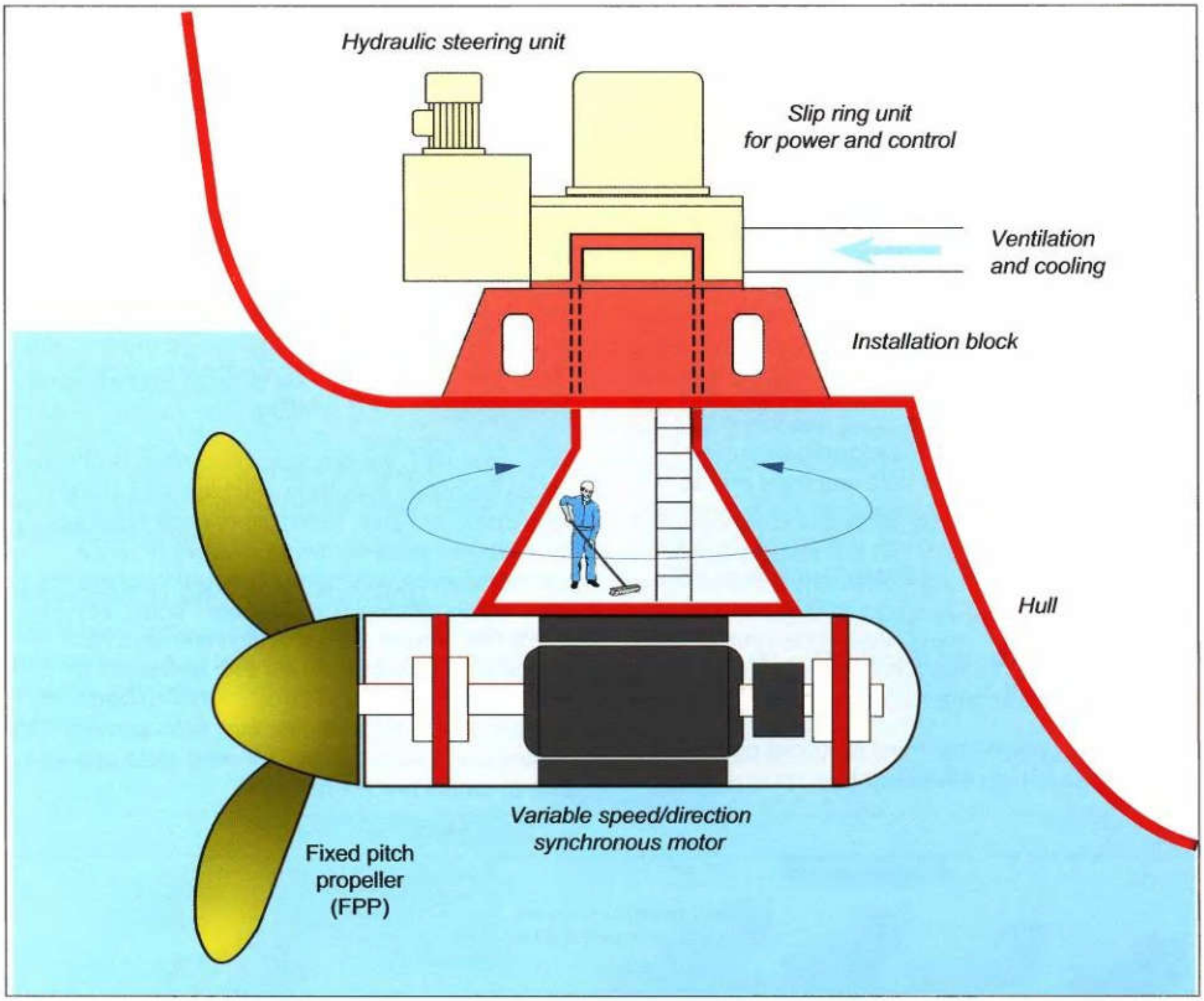


Figure 8.4 - Azipod drive unit

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.

8.2 Power Supply Network

As the demand for electrical power increases on ships (particularly passenger ferries, cruise liners, 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.

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, eg 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.

For example, a three-phase 6 MW ship's load on a 440 V system supplied by 3 × 2 MW, 0.8 pf diesel generator units requires the switchboard fault level to be about 90 kA and each generator circuit breaker and system cabling has to handle a full-load current (FLC) of:

$$I = \frac{P}{\sqrt{3} \times V \times \cos\varphi} = \frac{2{,}000{,}000\ W}{\sqrt{3} \times 440\ V \times 0.8} = \mathbf{3280\ A}$$

The same system at 6.6 kV requires the HV switchboard and cables to be rated for a fault level of about 9 kA with generator circuit breakers rated only for an FLC of 220 A.

$$I = \frac{P}{\sqrt{3} \times V \times \cos\varphi} = \frac{2{,}000{,}000\ W}{\sqrt{3} \times 6600\ V \times 0.8} = \mathbf{219\ A}$$

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 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 Figure 8.5. 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 produce 6.6 kV, 60 Hz three-phase AC voltages.

The principal consumers are the two synchronous AC 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

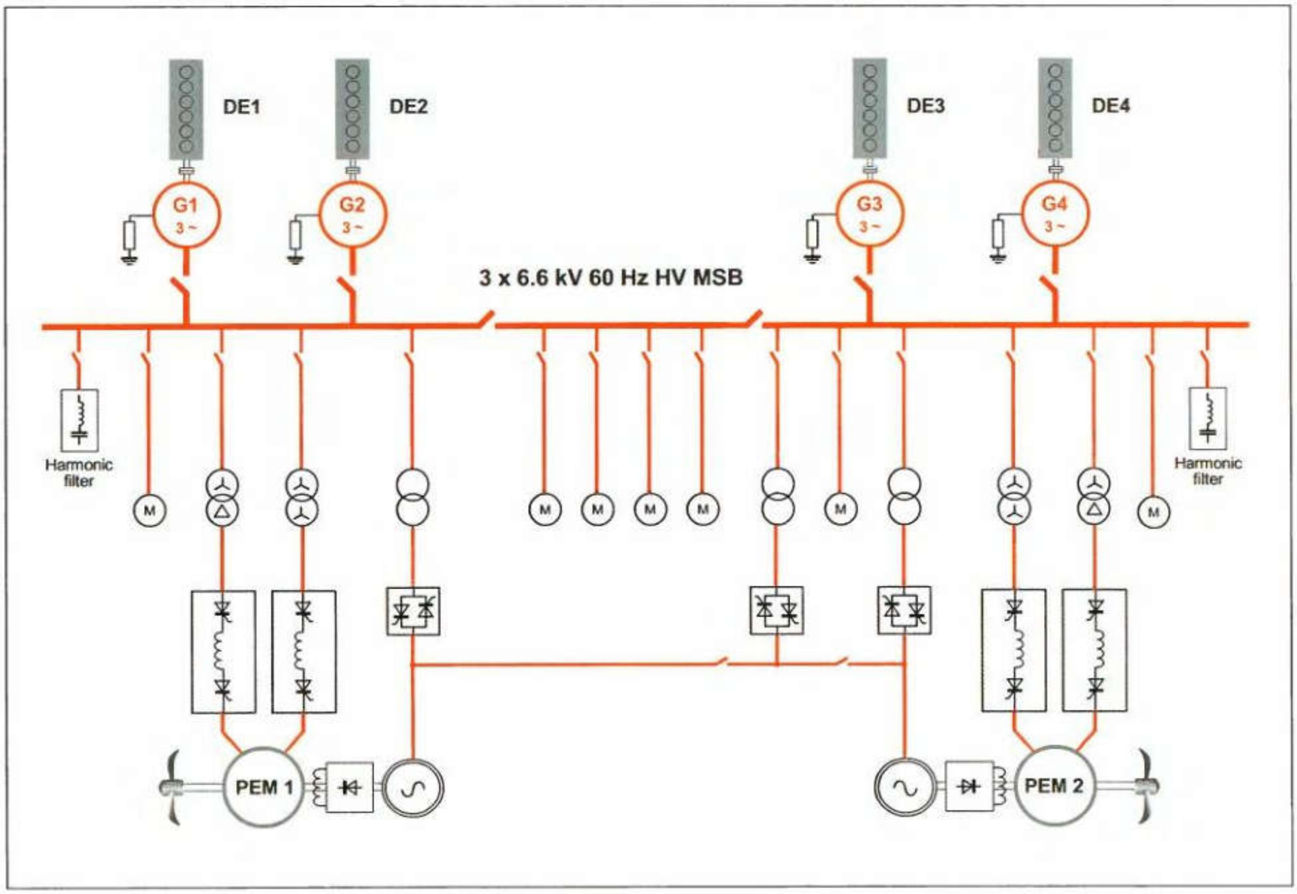


Figure 8.5 - HV power system

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 HV main switchboard with the vacuum breakers. These are:

- Two forward thrusters and one aft thruster
- three air conditioning compressors.

Other main feeders supply the 440 V low voltage main switchboard (LV MSB) via step-down transformers. An interconnector cable links the ER sub to the emergency switchboard. Other 440 V sub-stations (accommodation, galley, etc) around the ship are supplied from the LV MSB. Some installations may feed the ship's sub-stations directly with HV and step-down to 440 V locally.

The PEM drives in this example are synchronous motors that require a controlled low voltage excitation supply current to magnetise the rotor poles. This supply is obtained from the HV switchboard via a step-down transformer, but an alternative arrangement would be to obtain the excitation supply from the 440 V ER main switchboard.

QUESTION

Assuming 100% efficiency, calculate the FLC then estimate the DOL starting current for a three-phase, 100 kW, 0.9 pf induction motor supplied at:

(a) 440 V

(b) 6.6 kV.

ANSWER

(a) 145.8 A, 729 A

(b) 9.7 A, 49 A (assuming $I_{DOL} = 5 \times I_{FLC}$)

8.3 Review of Motor Operation

Electric motors for ship propulsion may be either DC or AC. The AC versions may be induction or synchronous models.

DC Motors

DC motor drives are still used where very high torque and/or precise speed control is acquired. Traction drives, such as electric trains, submarines and offshore drilling rigs, use DC motors. The torque is governed by $T = \Phi \times I_A$ and the speed is due to $n = V/\Phi$, where Φ is the magnetic field flux and I_A is the armature current (see Figure 8.6).

As the armature current and field flux can be independently controlled, the DC motor is able to provide very useful torque/speed characteristics for power drives.

The major drawback of a DC motor is that the necessary switching of the armature current is achieved by a mechanical 'commutator' on the rotating shaft. Apart from the maintenance required for the commutator and its carbon brushes, the applied voltage for the armature is limited to about 750 V DC voltage.

AC Motors

Induction Type

The most common motor drive is a three-phase AC induction motor with a cage rotor, because it is extremely robust as there are no electrical connections to the rotor (see Figure 8.7).

Three time-displaced supply currents to the three stator windings produce a rotating magnetic field that induces currents into the cage winding on the rotor. The interaction of stator flux Φ and rotor current I_R produces a torque on the shaft from $T = \Phi \times I_R \times \cos\varphi$, where φ is the phase angle between Φ and I_R. To be able to induce currents into the rotor, its running speed must be slightly lower than that of the stator rotating field. This difference is called the slip speed and ranges between about 1-5% over the load range for a standard induction motor.

The speed n_s of the rotating flux produced by the stator is fixed by the number of winding pole-pairs 'p' and the supply frequency 'f' as: $n_s = f/p$ (rev/s).

For example:

For a motor designed for 4-poles (p = 2) to run on a 50 Hz supply with a full-load slip of 4%, the speed of the rotating flux is:

$n_s = 50/2 = 25$ rev/s (1500 rev/min),

but the actual rotor speed will be:

$n_R = 96\%$ of 25 = **24 rev/s** or **1440** rev/min.

While the cage type induction motor is simple and low cost, it has some practical disadvantages. When supplied with a fixed voltage and frequency, the motor runs at an almost constant speed and has a high starting current of up to seven times its full load value.

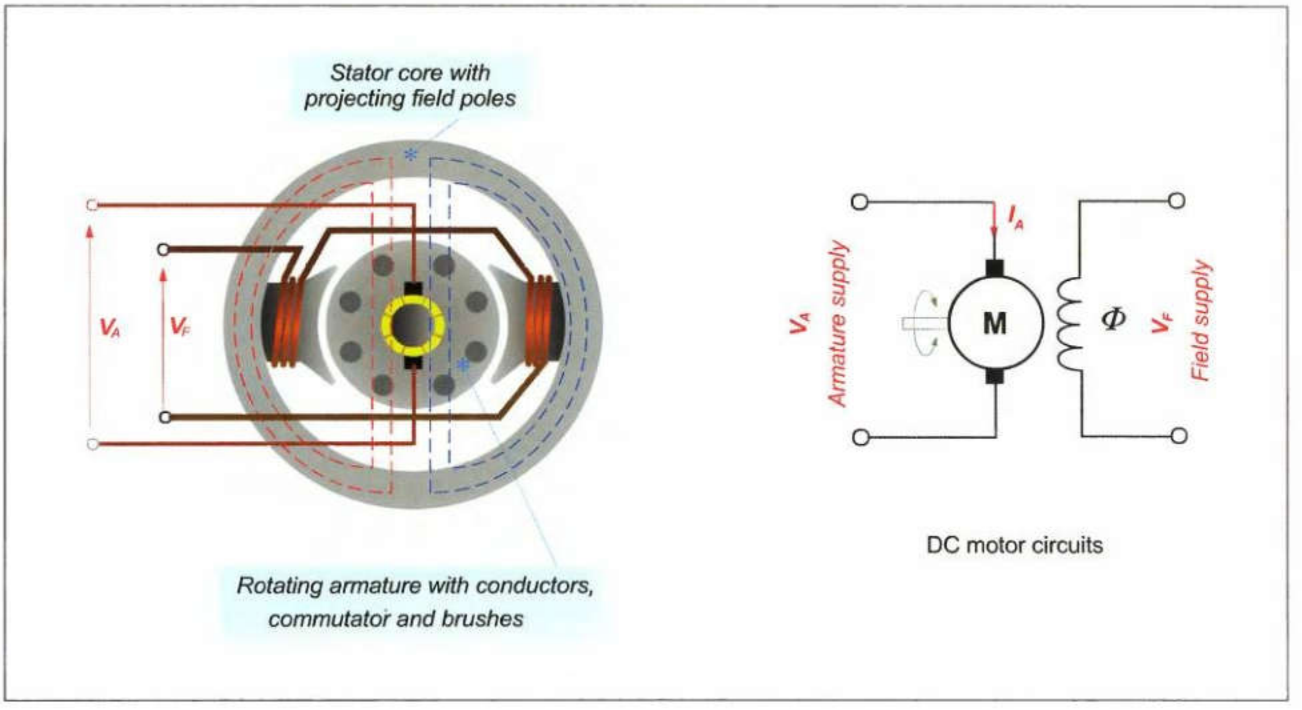


Figure 8.6 - DC motor circuit

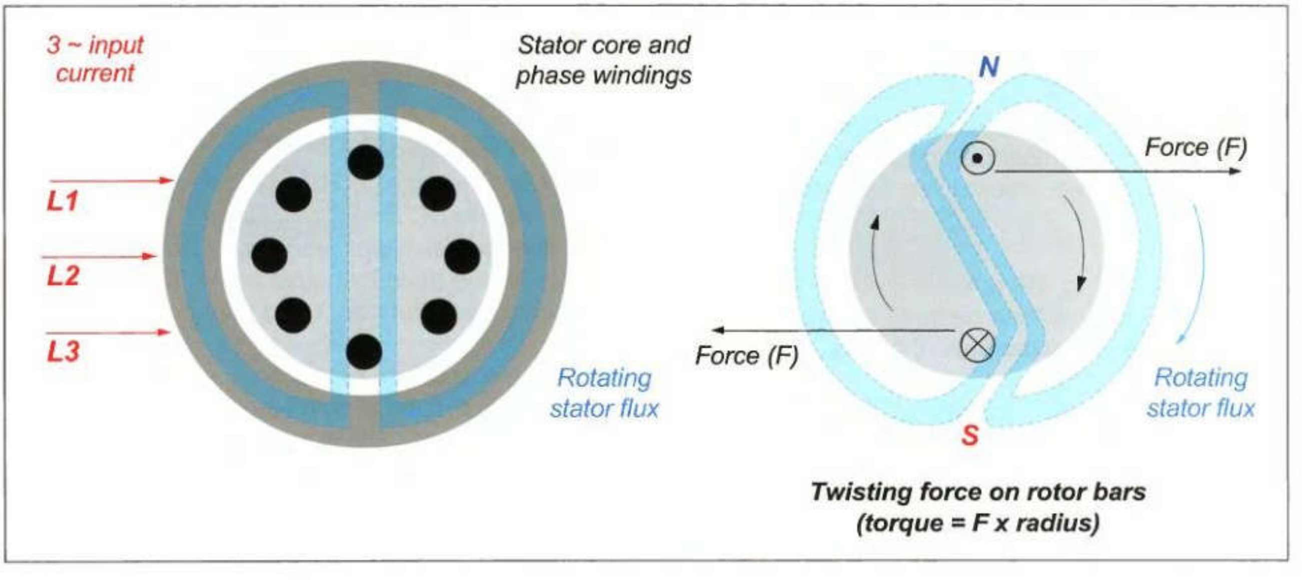


Figure 8.7 - Induction motor action

If the motor in the above example is designed for 440 V with a full load rated output of 100 kW, an efficiency of 90% and a power factor of 0.8 lagging, its full load supply current will be found from the three-phase power formula:

$P = \sqrt{3} \times V_L \times I_L \times \cos\varphi$
the electric power input is 100/90% = 111.1 kW
and

$I_L = (111.1 \times 10^3)/\sqrt{3}.440 \times 0.8 = 182.2$ A
then the initial starting current surge is about **911 A**.

Synchronous Type

This is a three-phase motor that produces a magnetic field rotating at a speed of $n_s = f/p$ (rev/s), just like the induction motor type.

The rotor has a set of magnetic poles with DC excitation that locks in synchronism with the stator rotating flux.

This means that the shaft is always running at the synchronous speed set by the supply frequency (see Figure 8.8).

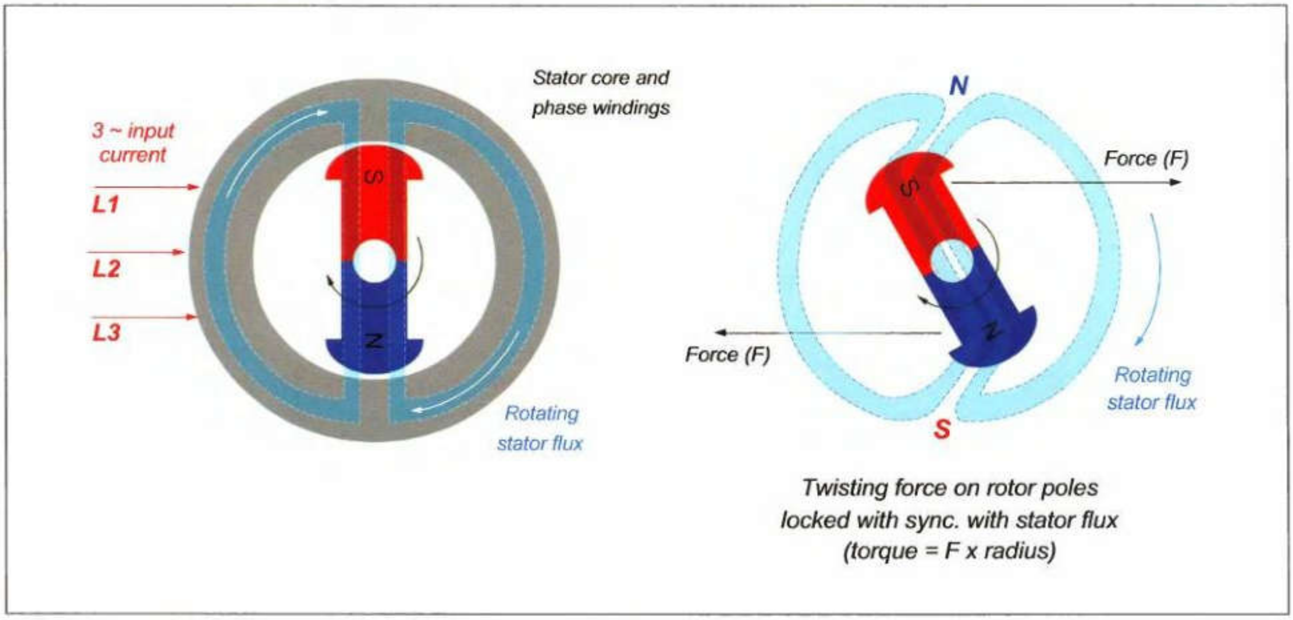


Figure 8.8 - Synchronous motor action

To start the motor from standstill can be a problem – it is either:

- Pulsed forward at a very low frequency with the rotor poles excited, or
- dragged up to slip speed as an induction motor with an embedded cage rotor, then locked into synchronism by energising the DC rotor field.

For normal running, the operating power factor of a synchronous motor can be lagging or leading as this is determined by the size of the DC excitation field current.

Basic speed control of motors

Many industrial installations can benefit from direct and smooth speed control of a drive that is moving the process material (water, compressed air, oil, conveyor belts, lifts, etc). Smooth, controlled acceleration and deceleration also reduces shock loading in the system. For a DC motor on a fixed voltage supply, this is achieved by using resistance in the armature or field circuits to control the armature current or field flux (or both). The disadvantage is the overall loss of efficiency due to the power losses in the external control resistance(s).

For an AC induction motor or synchronous motor on a fixed voltage and frequency supply, resistance control would only affect the size of operating current, but the speed is constant due to the fixed supply frequency. This can only be overcome by changing the frequency of the stator supply currents. To prevent overheating (by over-fluxing) of the motor while frequency changing, the supply voltage must be changed in direct proportion.

Advanced speed control

Computer-controlled variable speed drives (VSDs) are applied to DC and AC motor types of all sizes. The most popular application is for induction motors for the main industrial power range, but synchronous motors are used in large installations.

The AC motor drives produce a variable frequency output by fast voltage switching from a transistor or thyristor converter, which may be AC/DC/AC (PWM and synchroconverter) or AC/AC (cycloconverter). These drives use a mathematical model of the motor and the computer controls the converter output to precisely match the set inputs for speed, torque, acceleration, deceleration, power limits, etc.

Drives may be tuned to create optimum conditions for run-up/down, braking and energy savings against the connected shaft load.

Problems arising

The fast switching (or chopping) of the voltages to VSDs will produce a distorted waveform that includes high frequency harmonic components whose frequencies are exact multiples of the fundamental (base frequency) value.

For example, a 7th harmonic of a 60 Hz fundamental will be at 420 Hz. Such harmonics create additional heating in equipment and possible interference (often called radio frequency interference or RFI).

Practical solutions to a harmonic problem include good initial system design, filtering and suppression.

8.4 Controlled Rectification and Inversion

The generated three-phase AC electrical power supply on a ship has a fixed voltage and frequency. This is generally at 440 V and 60 Hz, but for high power demands it is likely to be 6.6 kV and 60 Hz.

Speed control for a propulsion motor requires variable voltage for a DC drive and variable frequency + voltage for an AC drive. The set busbar AC voltage must be converted by controlled rectification (AC/DC) and/or controlled inversion (DC/AC) to match the propulsion motor type.

A basic rectifier uses semiconductor diodes that can only conduct current in the direction of anode (A) to cathode (K), and this is automatic when A is more positive than K. The diode turns off automatically when its current falls to zero. Therefore, in a single-phase AC circuit, a single diode will conduct only on every other half-cycle, called half-wave rectification. Other single-phase circuits, using a bi-phase arrangement with two diodes and a centre tapped transformer, will create full wave rectification. Similarly, four diodes in a bridge formation will also produce a full wave DC voltage output. An equivalent three-phase bridge requires six diodes for full wave operation. A diode, having only two terminals, cannot control the size of the DC output from the rectifier.

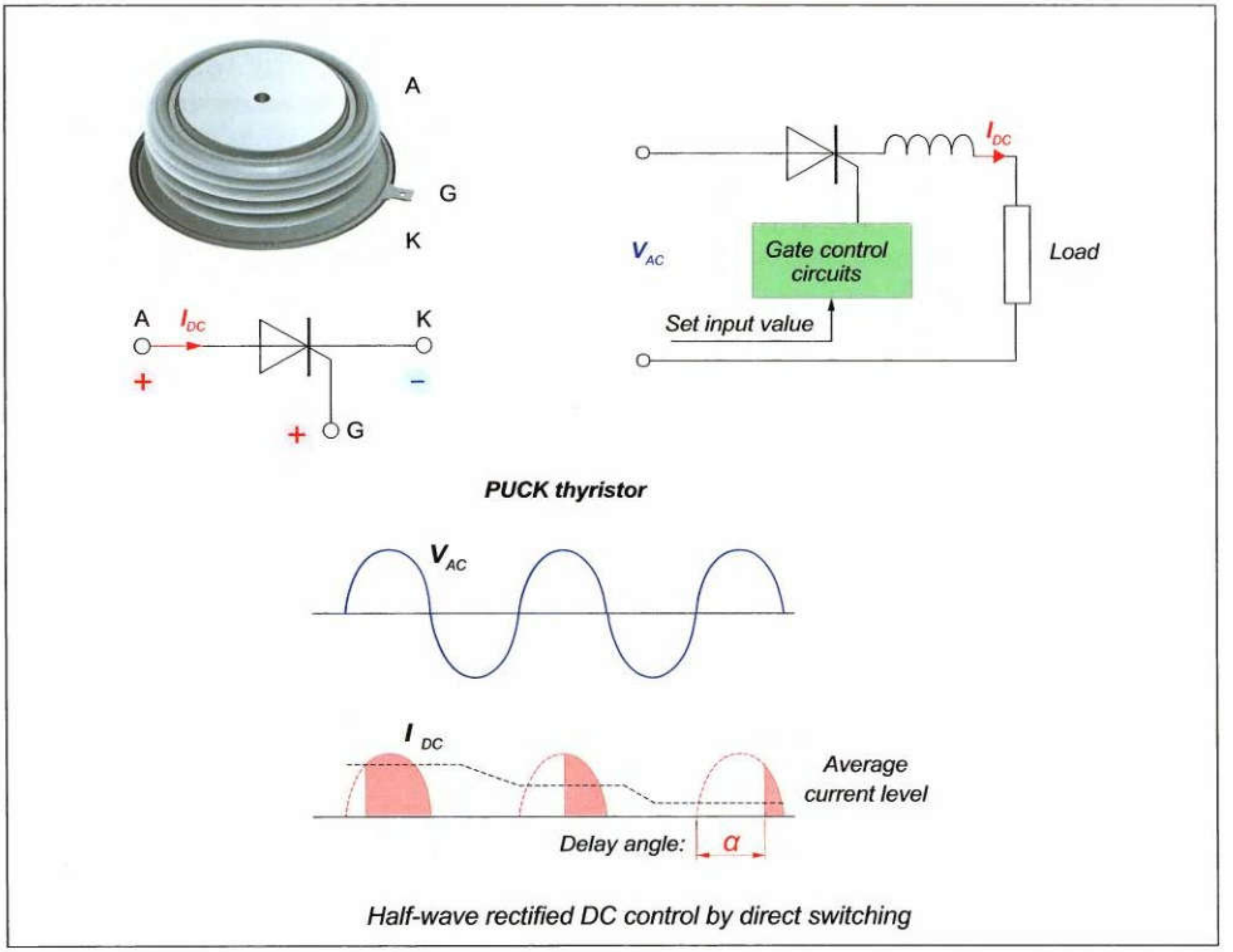


Figure 8.9 - Single-phase controlled rectification

Controlled Rectification Process

For controlled rectification, it is necessary to use a set of three terminal devices such as thyristors (for high currents) or transistors (for low–medium currents).

A basic AC/DC control circuit using a thyristor switch is shown in Figure 8.9. Compared with a diode, a thyristor has an extra (control) terminal called the gate (G). The thyristor will only conduct when the anode is positive with respect to the cathode and a brief trigger voltage pulse is applied between gate and cathode (gate must be more positive than cathode). Gate voltage pulses are provided by a separate electronic circuit and the pulse timing decides the switch-on point for the main (load) current. The load current is, therefore, rectified to DC (by diode action) and controlled by delayed switching. In this circuit, an inductor coil (choke) smooths the DC load current even though the DC voltage is severely chopped by the thyristor switching action. An alternative to the choke coil is to use a capacitor across the rectifier output, which smooths the DC voltage.

Full wave controlled rectification from a three-phase AC supply is achieved in a bridge circuit with six thyristors, as shown in Figure 8.10.

For a 440 V (rms) AC line voltage, the peak voltage is $440 \times \sqrt{2} = 622$ V. The equivalent maximum DC average voltage output is taken to be about 600 V as it has a six-pulse ripple effect due to the three-phase input waveform.

Controlled Inversion Process

A DC voltage can be inverted (switched) repeatedly from positive to negative to form an alternating (AC) voltage by using a set of thyristor (or transistor) switches. A controlled three-phase thyristor bridge inverter is shown in Figure 8.11.

The inverter bridge circuit arrangement is exactly the same as that for the rectifier. Here, the DC voltage is sequentially switched onto the three output lines. The rate of switching determines the output frequency. For AC motor control, the line currents are directed into (and out of) the windings to produce a rotating stator flux wave that interacts with the rotor to produce torque.

8.5 Converter Types

The processes of controlled rectification and inversion are used in converters that are designed to match the drive motor. The principal types of motor control converters are:

- AC/DC (controlled rectifier for DC motors)
- AC/DC/AC (PWM for induction motors)
- AC/DC/AC (synchroconverter for synchronous motors)
- AC/AC (cycloconverter for synchronous motors).

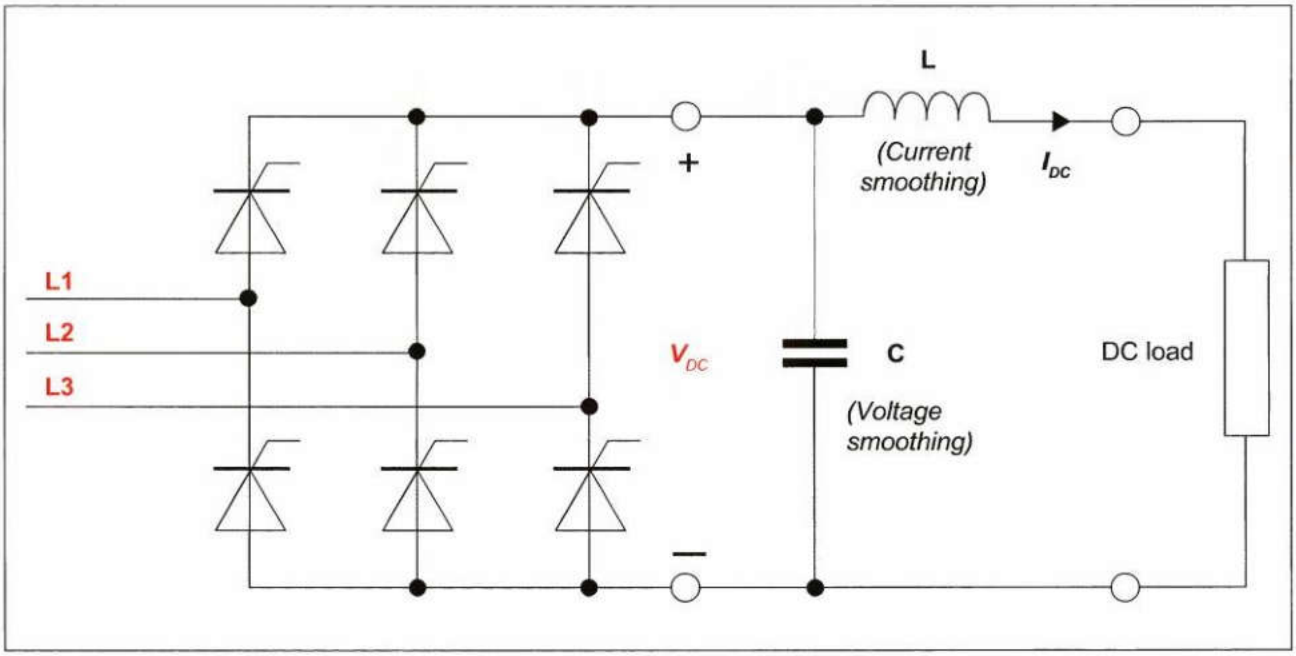


Figure 8.10 - Three-phase controlled rectifier bridge circuit

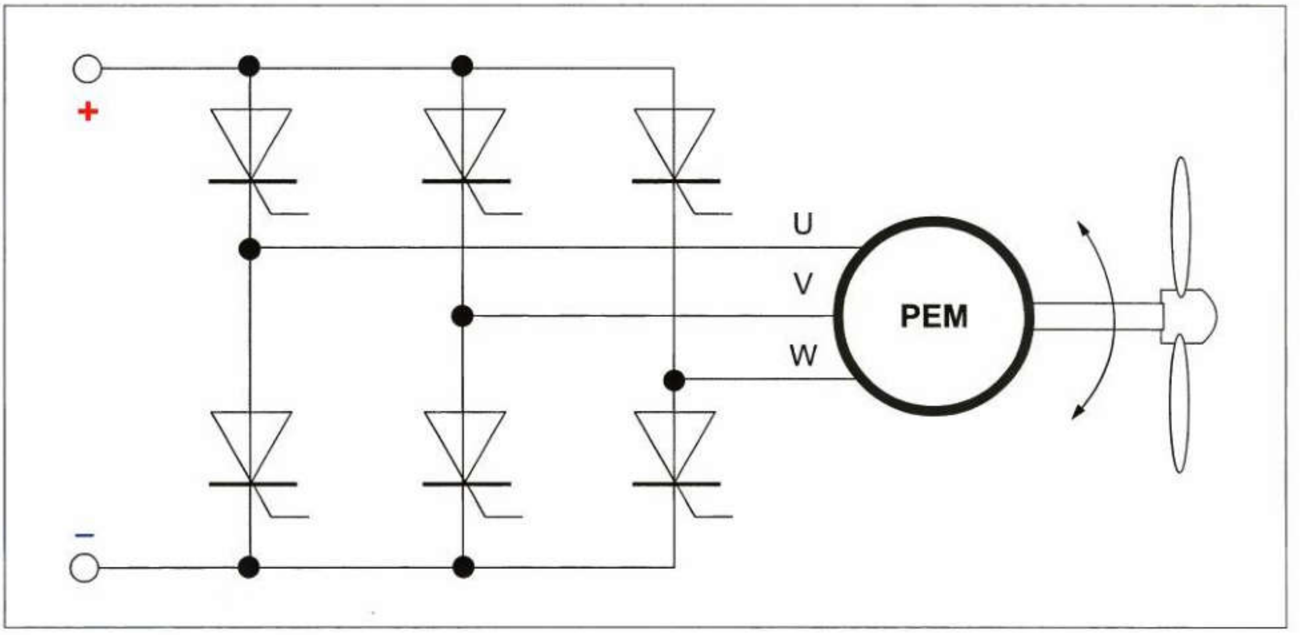


Figure 8.11 - Three-phase inverter circuit and AC synchronous motor

AC/DC Converter

This is a three-phase AC controlled rectification circuit for a DC motor drive. Two converters of different power ratings are generally used for the separate control of the armature current (I_A) and the field current that produces the magnetic flux (Φ). Some systems may have a fixed field current, which means that the field supply only requires an uncontrolled diode bridge, as shown in Figure 8.12.

Motor torque is determined from $T = \Phi \times I_A$ and the speed is controlled from $N = V_A/\Phi$. Shaft rotation can be achieved by reversing either the field current or the armature current direction. Ship applications for such a drive would include

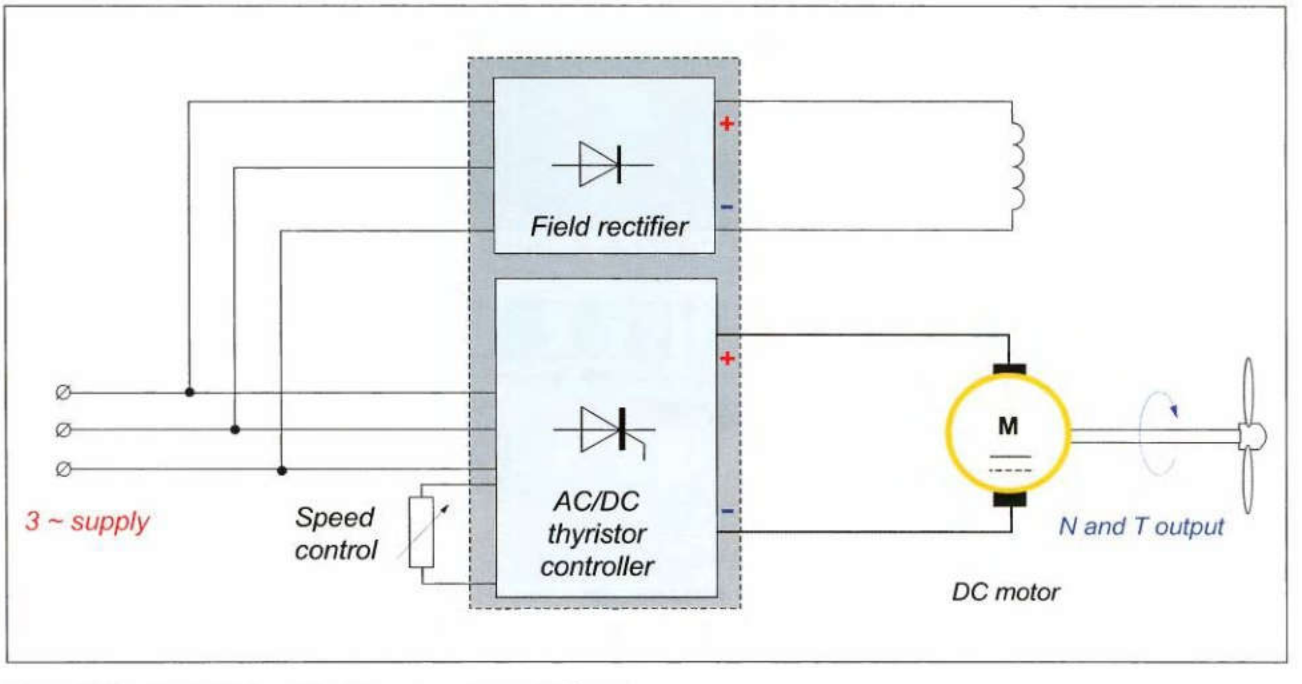


Figure 8.12 - Controlled rectification converter and DC motor

cable-laying, offshore drilling, diving and supply, ocean survey and submarines.

AC/DC/AC PWM Converter

This type of converter is used for induction motor drives and uses transistors as the switching devices. Unlike thyristors, a transistor can be turned on and off by a control signal and at a high switching rate (eg at 20 kHz in a PWM converter), as shown in Figure 8.13.

The input rectifier stage is not controlled so is simpler and cheaper, but the converter will not be able to allow power from the motor load to be regenerated back into the mains supply during a braking operation. From a 440 V AC supply, the rectified DC (link) voltage will be smoothed by the capacitor to approximately 600 V.

The DC voltage is chopped into variable width, but constant level, voltage pulses in the computer-controlled inverter section using IGBTs. This process is called pulse width modulation or PWM. By varying the pulse widths and polarity of the DC voltage, it is possible to generate an averaged sinusoidal AC output over a wide range of frequencies, typically 0.5-120 Hz. Due to the smoothing effect of the motor inductance, the motor currents appear to be nearly sinusoidal in shape. By sequentially directing the currents into the three stator windings, a reversible rotating magnetic field is produced with its speed set by the output frequency of the PWM converter.

Accurate control of shaft torque, acceleration time and resistive braking are some of the operational parameters that can be programmed into the VSD, usually via a handheld unit. The VSD can be closely tuned to the connected motor drive to achieve optimum control and protection limits for the overall drive. Speed regulation against load changes is very good and can be made very precise by the addition of feedback from a shaft speed encoder.

VSDs, being digitally controlled, can be easily networked to other computer devices, eg programmable logic controllers (PLCs), for overall control of a complex process.

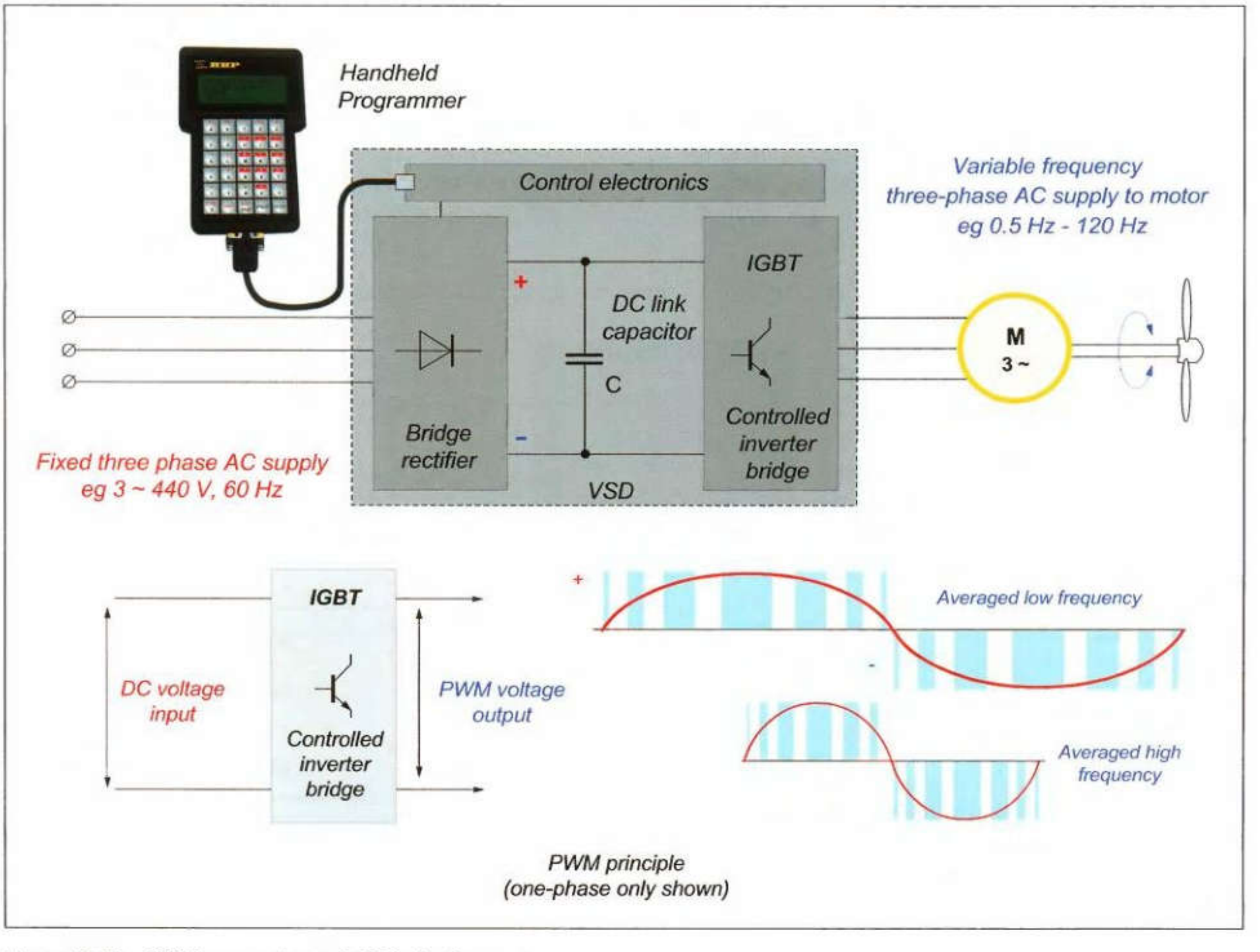


Figure 8.13 - PWM converter and AC induction motor

AC/DC/AC Synchroconverter

This type of converter is used for large AC synchronous motor drives (called a synchrodrive) and is applied very successfully to marine electric propulsion.

A synchroconverter, as shown in Figure 8.14, has controlled rectifier and inverter stages that both rely on natural turn-off (line commutation) for the thyristors by the three-phase AC voltages at either end of the converter. Between the rectification and inversion stages is a current smoothing reactor coil forming the DC link.

An operational similarity exists between a synchrodrive and a DC motor drive. This view considers the rectifier stage as a controlled DC supply and the inverter/synchronous motor combination as a DC motor. The switching inverter acts as a static commutator.

The combination of controlled rectifier and DC link is considered to be a current source for the inverter, whose task is then to sequentially direct blocks of the current into the motor windings, as shown in Figure 8.15.

The size of the DC current is set by the controlled switching of the rectifier thyristors. Motor supply frequency (and therefore its speed) is set by the rate of inverter switching. The six inverter thyristors provide six current pulses per cycle (known as a six-pulse converter).

A simplified understanding of synchroconverter control is that the current source (controlled rectification stage) provides the required motor torque and the inverter stage controls the required speed. To provide the motor EMF, which is necessary for natural commutation of the inverter thyristors, the synchronous motor must have rotation and magnetic flux in its rotor poles. During normal running, the synchronous motor is operated with a power factor of about 0.9 leading (by field excitation control) to assist the line commutation of the inverter thyristors. The DC rotor field excitation is obtained from a separate controlled thyristor rectification circuit.

As the supply (network) and machine bridges are identical and are both connected to a three-phase AC voltage source, their roles can be switched into reverse. This is useful to allow the regeneration of motor power back into the mains power supply that provides an electric braking torque during a sudden stop of the ship.

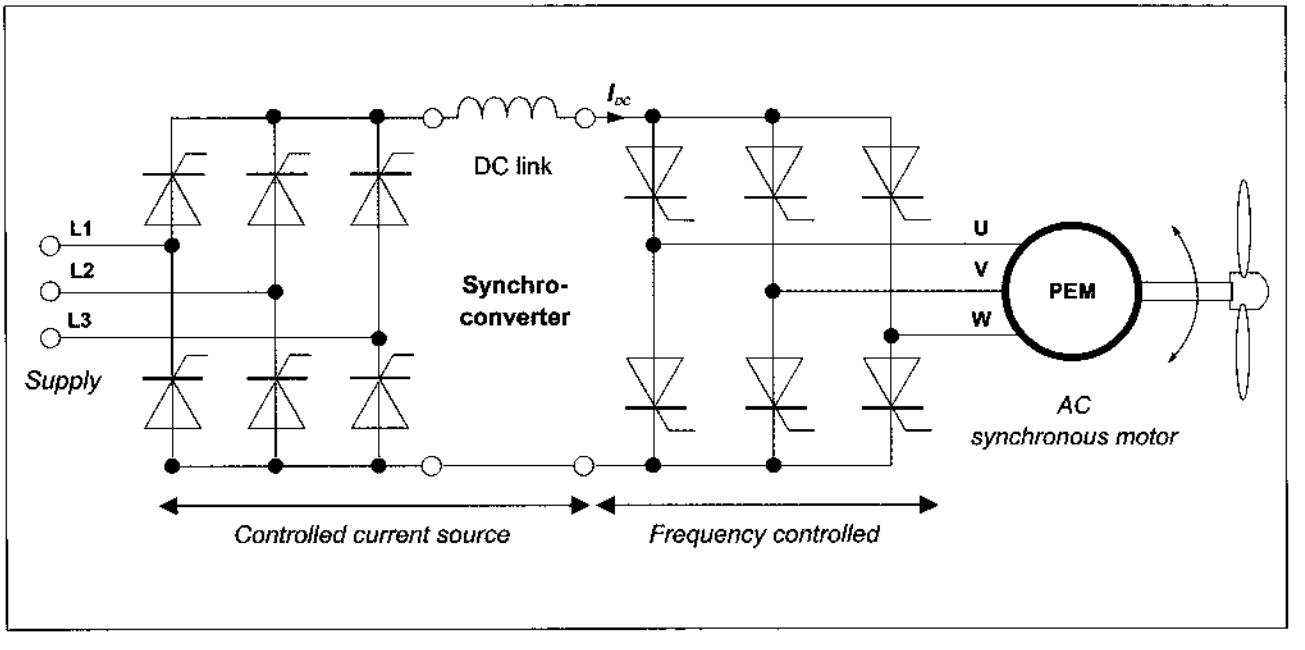


Figure 8.14 - Synchroconverter circuit

AC/AC Cycloconverter

While a synchroconverter is able to provide an output frequency range typically up to twice that of the mains input (eg up to 120 Hz), a cycloconverter is restricted to a much lower range. This is limited to less than a third of the supply frequency (eg up to 20 Hz), which is due to the way in which this type of converter produces the AC output voltage waveform. Ship propulsion shaft speeds are typically in the range of 0-145 rev/min, which can easily be achieved by the low frequency output range of a cycloconverter to a multi-pole synchronous motor. Power regeneration from the motor back into the main power supply is available.

A conventional three-phase converter from AC to DC can be controlled so that the average output voltage can be increased and decreased from zero to maximum within a half-cycle period of the sinusoidal AC input. By connecting two similar converters back to back in each line, an AC output frequency is obtained. The switching pattern for the thyristors varies over the frequency range which requires a complex computer program for converter control.

Figure 8.16 shows a basic circuit arrangement for a cycloconverter together with an approximate voltage waveform for the low frequency output. The corresponding current waveform shape (not shown) will be more sinusoidal due to the smoothing effect of motor and line inductance.

The output voltage has a significant ripple content that gets larger (worse) as the output frequency is raised. It is this feature that limits the maximum useful frequency.

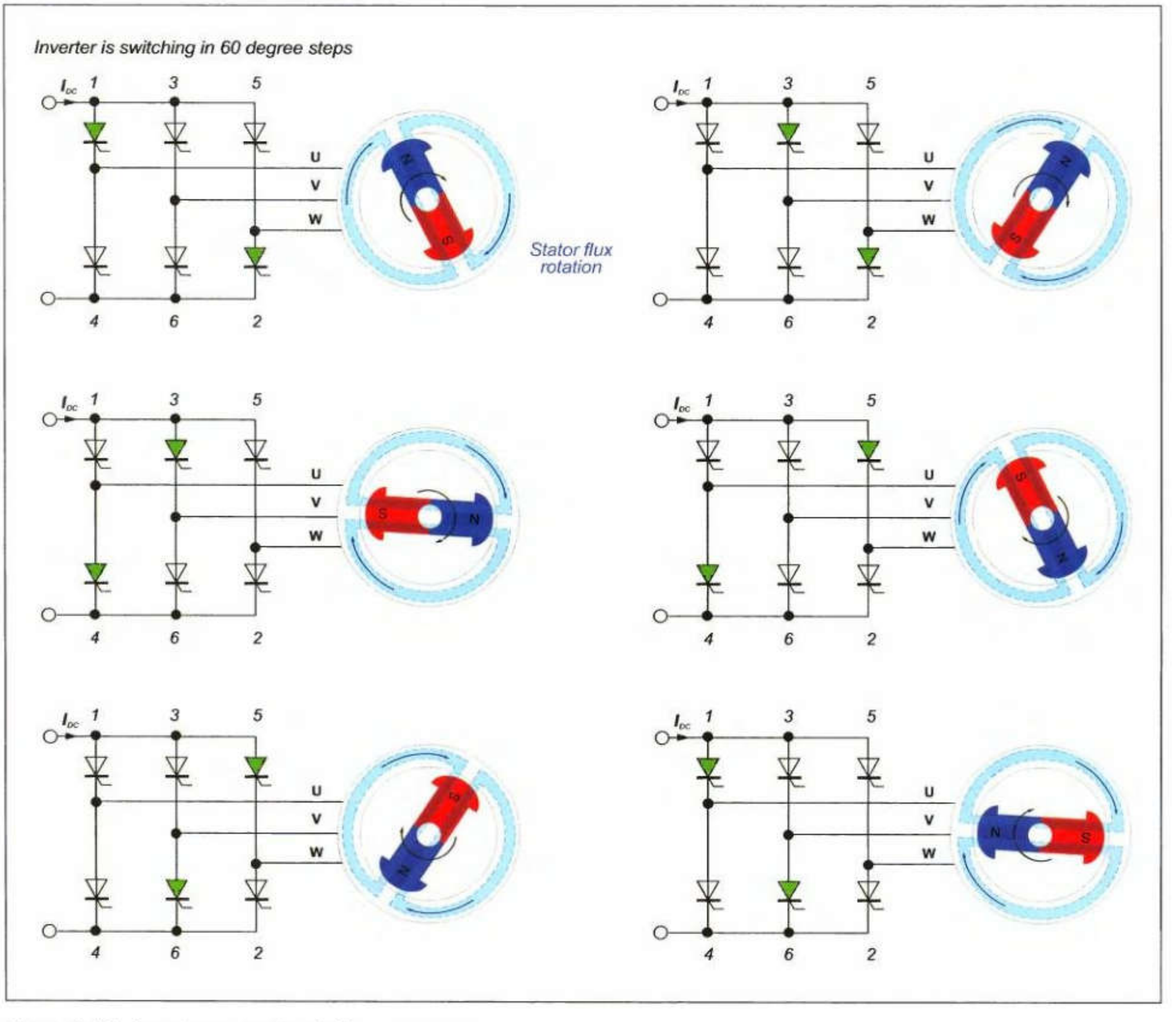


Figure 8.15 - Inverter current switching sequence

There is no connection between the three motor windings because the line converters have to be isolated from each other to operate correctly to obtain line commutation (natural) switching of the thyristors.

The converters may be directly supplied from the HV line, but it is more usual to interpose step-down transformers. This reduces the motor voltage and its required insulation level while providing additional line impedance to limit the size of prospective fault current and harmonic voltage distortion at the main supply busbar.

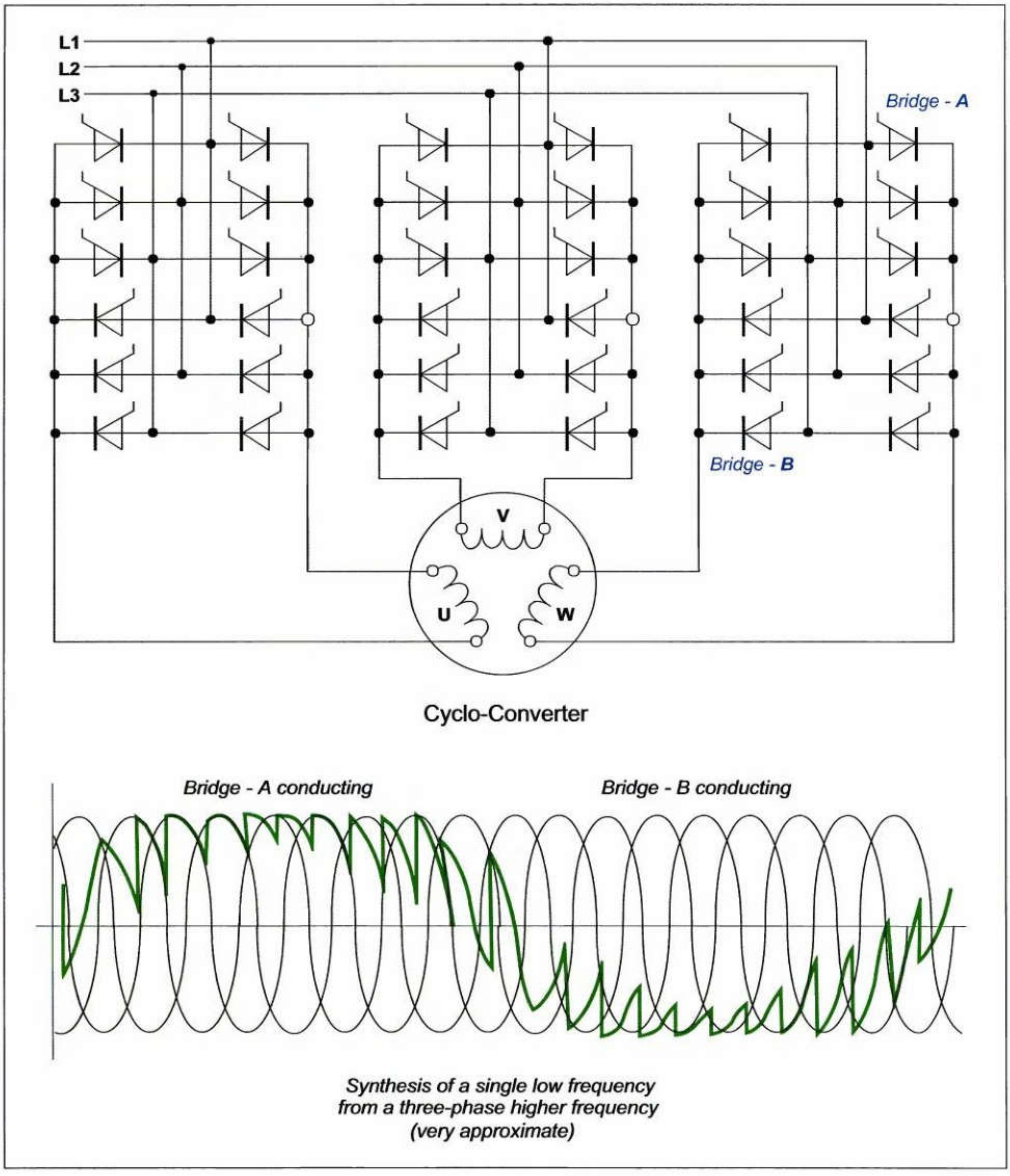


Figure 8.16 - Cycloconverter circuit and output voltage waveform

8.6 Propulsion System Operation

This section describes the overall operation of a propulsion system and is based on a diesel-electric arrangement with synchroconverter frequency control. For a large ship, the power system will employ HV generation, as in the diagram in Figure 8.17.

In this example, each 12 MW, 3 kV propulsion motor has two separate 6 MW stator windings and each half winding is supplied from a 6.6/3.0 kV propulsion transformer and a static 6-pulse synchroconverter. The 24-pole motors have a shaft speed range of 0-145 rev/min controlled from the converter output frequency range of 0-29 Hz.

By using two converters feeding two separate stator windings fitted 30° apart, a 12-pulse shaft torque is achieved to minimise shaft vibration. A more complicated arrangement of supply transformers and converters can produce a 24-pulse shaft torque.

Motor brushless excitation is also obtained from the HV busbars via a 6.6/0.44 kV static transformer, a thyristor controller, an AC/AC rotary transformer (inside the motor) and a set of shaft-mounted diodes for the final conversion to DC. A third (standby) static excitation supply and controller is available, but is not shown in the diagram.

The related physical arrangement of the main components in the propulsion system are shown in Figure 8.18.

Control throttle stations for both shafts are installed on the bridge (in the wheelhouse and on the wings), engine control room and local (in HV switchboard room) positions. At sea, the shaft speed commands are set from the bridge and repeated in the ECR. In port, the control position is transferred to the ECR. The local control position is mainly used for testing and maintenance duties, but also acts as an emergency control station. Selection of the command position is determined by a switch on the propulsion console in the ECR.

An emergency telegraph giving set speed commands (dead-slow, half-ahead, etc) is available at each control station. The ship propulsion regulator and side thruster regulators can be combined into a master joystick controller to give overall directional control for accurate manoeuvring in port.

In a synchrodrive system, as shown in Figure 8.19, the central processing unit (not shown) receives a command (set speed) input and many feedback signals (voltage, current, power, frequency, etc), but the main regulating item is the actual shaft speed feedback forming a closed control loop. The principal parameters to be controlled are the size of motor stator current (to set motor torque) and the motor frequency to set the shaft speed. In addition,

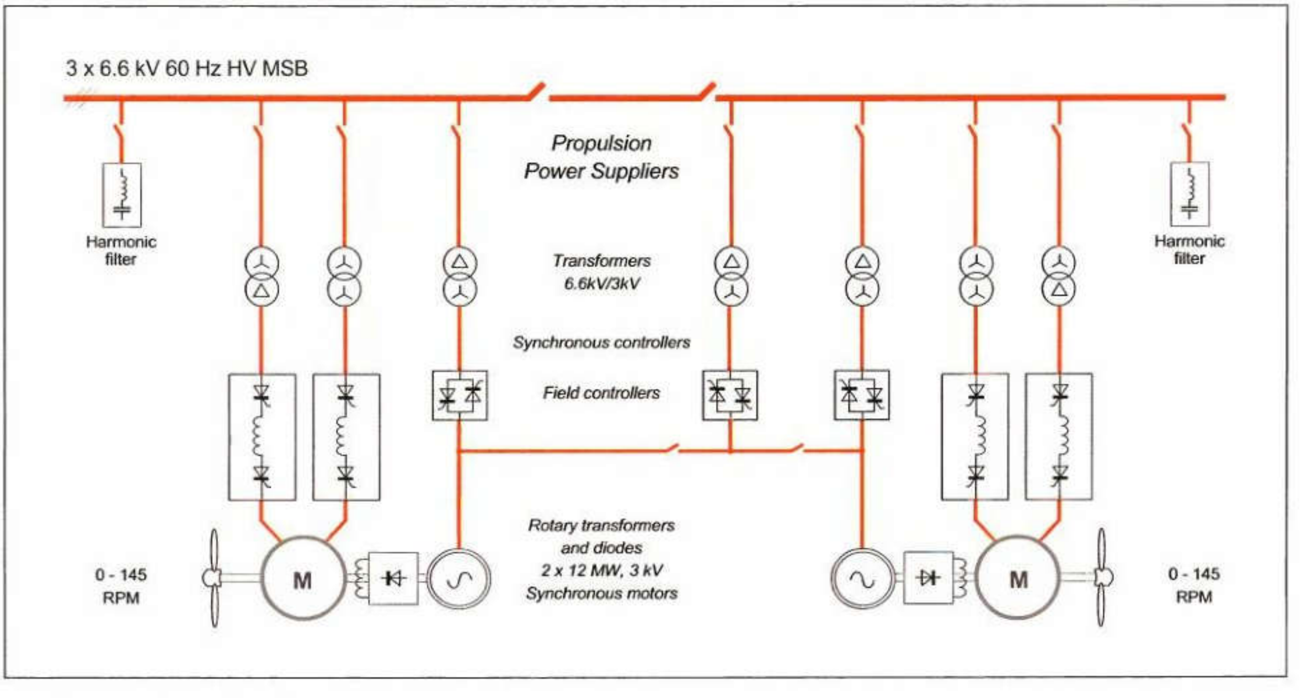


Figure 8.17 - HV propulsion power system

the DC motor field current has to be continually controlled from the propulsion regulator via the excitation converter.

In normal running and full away, with both propulsion motor speeds within 5% of each other, the bridge can select a shaft synchro phasing mode that applies momentary acceleration/deceleration to bring the propeller blades into an alignment that minimises shaft vibration into the hull.

Speed and position are derived from detectors on the non-drive end of the motor shaft. At speeds of less than 10%, the motor does not generate sufficient back EMF to cause automatic thyristor switch-off (line commutation).

Remember that a thyristor can only switch off when its current becomes zero.

This problem is overcome by pulse mode operation where the current is momentarily forced to zero by the thyristors in the controlled rectifier stage. This allows the inverter thyristors to turn off so that the controller can regain control. The decision is now which thyristor and which sequence of switching is required to maintain the required shaft direction of rotation. It is necessary to know exactly the position of the rotor poles and this is provided by the shaft position encoder for low speed, pulse mode operation. When kicked above 10% speed, the motor EMF will be large enough to allow the converter to revert to its normal line-commutation mode for synchronous operation.

QUESTION

If the individual inverter thyristors are not switched off (commutated) at the necessary instant, a serious problem arises. Explain the likely consequences.

ANSWER

If two or more inverter thyristors are unable to be switched off naturally, they will apply a full short-circuit fault path across the DC link.

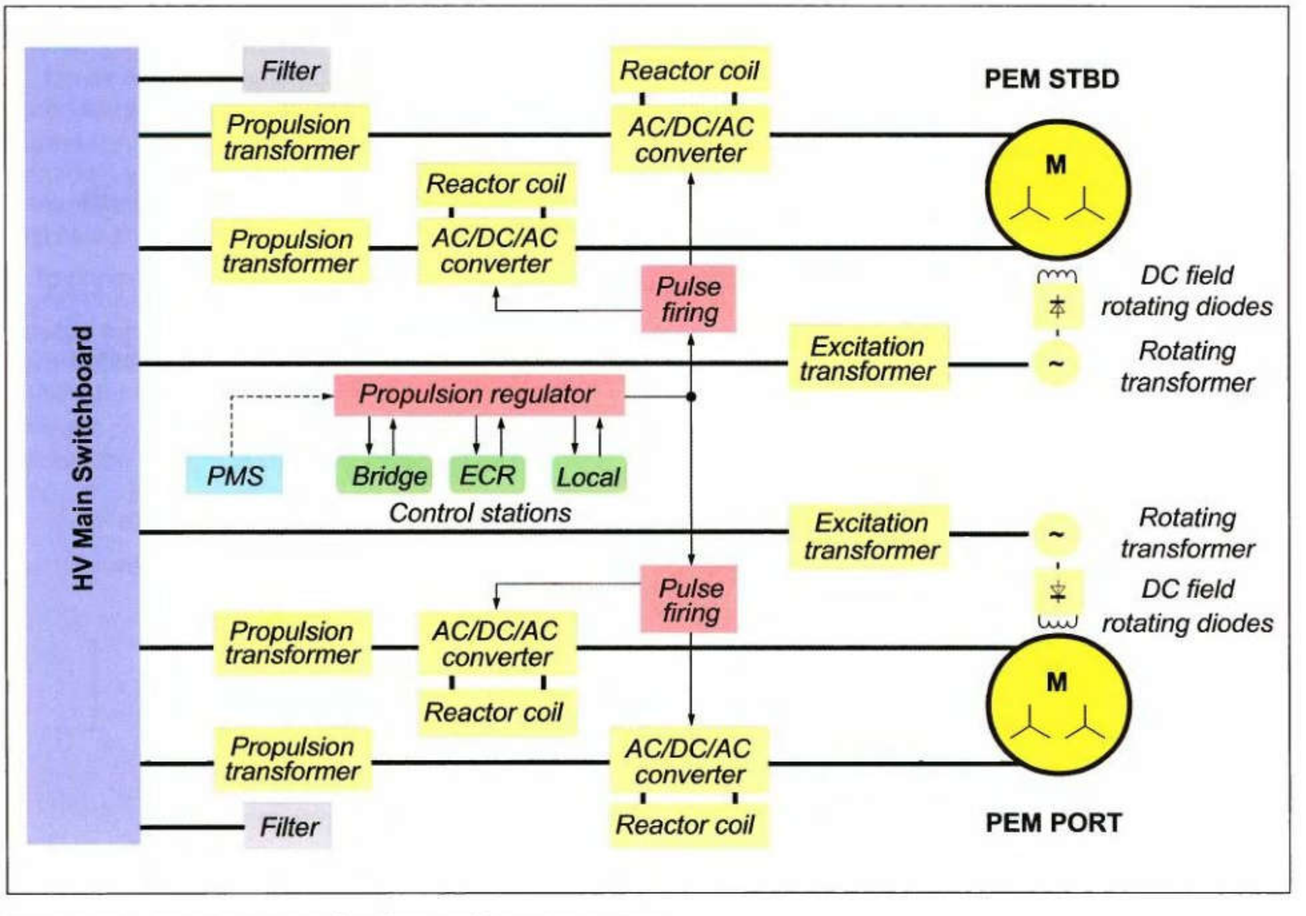


Figure 8.18 - Interconnection of main propulsion components

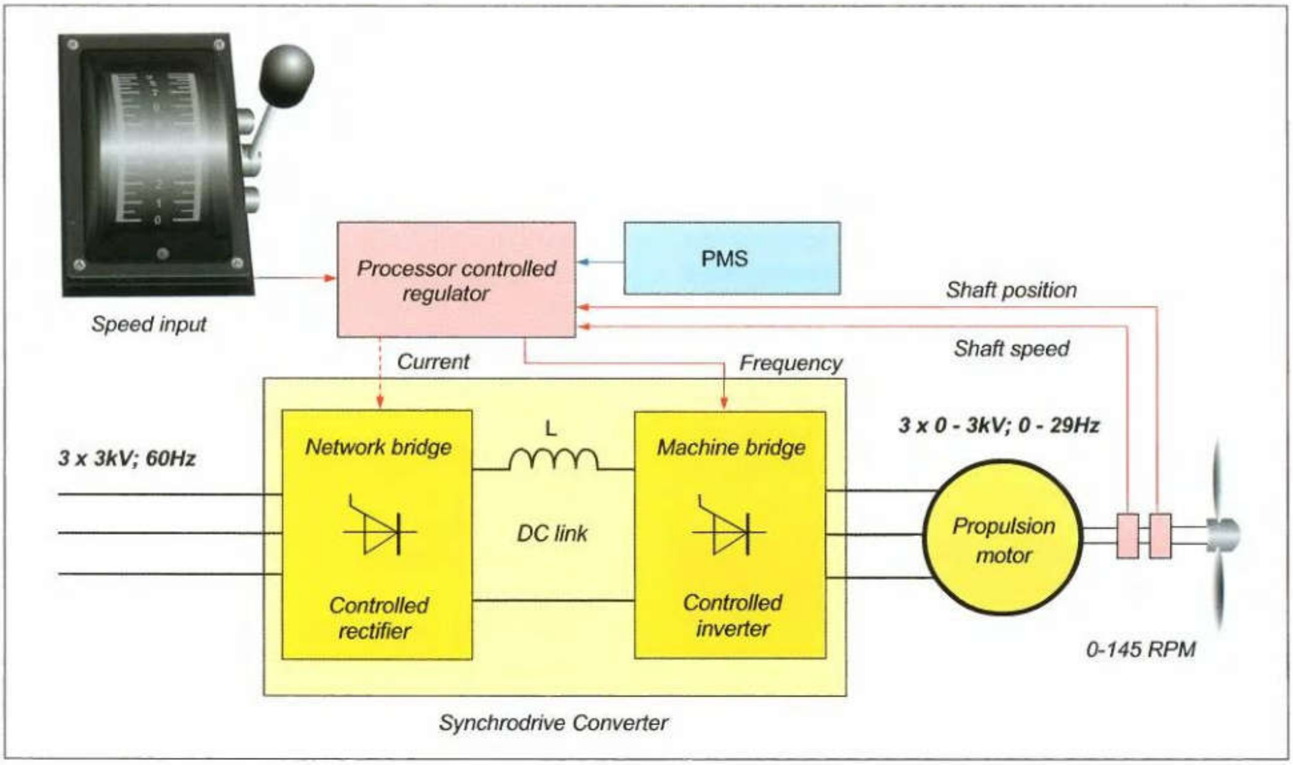


Figure 8.19 - Propulsion motor control scheme

For normal running, above about 10% speed, the operation is switched to synchronous mode where the thyristors in both bridges are switched off naturally (line commutated) by their live AC voltages from supply and motor.

To reverse the shaft rotation, the forward/ahead phase sequence of motor supply currents is reversed by the inverter thyristors. This reverses the direction of stator flux rotation and therefore shaft direction to astern. The rate of deceleration to zero speed must be carefully controlled before a shaft reversal to avoid large power surges in the system.

For a motor braking operation, the inverter bridge can be considered as a rectifier bridge when viewed from the live AC supply produced by the motor EMF. If the network (rectifier) bridge thyristors are switched with a delay angle greater than 90°, the DC link voltage reverses, causing power flow from the motor back to the supply (motor braking). In this mode, the roles of the network and machine bridges are swapped over.

Overall system power control is provided by a PLC-based power management system (PMS) that effectively coordinates power demand with its supply.

Broadly, the PMS functions are:

Control of:

- Automatic power limitation for propulsion motors
- auto-start, synchronising and load sharing of standby generators
- control of regeneration from the propulsion motors during braking and reversing manoeuvres
- power limitation for main generators
- load shedding by preferential tripping
- dynamic limitation of propulsion motor acceleration.

Monitoring of:

- Load sharing
- diesel performance
- proposal to start/stop a generator
- running time for generators and propulsion motors
- status and data display
- safety performance.

8.7 Harmonics

The input current to a static power converter generally has a high harmonic content due to the way the current is switched (chopped) from phase to phase. Harmonic currents are important because they cause distortion of the supply voltage waveform, which may result in the malfunction and additional heating of other equipment connected to the supply system.

The size and frequencies of the harmonic currents and voltages depend on the converter type, the pulse number and method of control (eg synchroconverter, cycloconverter or PWM).

Typical waveforms for a 6-pulse synchroconverter are shown in Figure 8.20.

Harmonic frequencies are generally integer multiples (eg 3, 5, 7, 11, 13, etc) of the fundamental (supply) frequency. Therefore, a 7^{th} harmonic in a 60 Hz AC voltage has a frequency of 420 Hz and an 11^{th} has a frequency of 660 Hz. Harmonic amplitudes are roughly the reciprocal of the harmonic number, ie 20% (1/5) for the fifth, 14.3% for the seventh, 9.1% for the eleventh, etc. The particular shape of the resulting supply voltage will depend on harmonic currents causing additional harmonic voltages in the supply reactance (inductive and/or capacitive). See the example in Figure 8.21.

Some harmonics are eliminated by careful system design, eg by adding more circuit inductance, using phase shifting transformers (star/star and star/delta) and increasing the converter pulse number. The 30° phase shifted transformers effectively double the current pulses drawn by the motor, so a 6-pulse converter system appears to be 12-pulse as viewed from the supply point.

For a generator sinusoidal AC voltage waveform with identical positive and negative shapes, all even-numbered harmonics are cancelled out. In a three-phase AC system, all harmonics that are a multiple of 3 are also automatically cancelled. That leaves harmonic numbers of 5^{th}, 7^{th}, 11^{th}, 13^{th}, 17^{th}, etc as potential problems. For a pair of 6-pulse synchroconverters supplied by a pair of phase shifted transformers, the significant harmonic problem is reduced to the 5^{th}, 11^{th} and 17^{th}.

The actual voltage waveshape can be examined with an oscilloscope or calculated into its harmonic content with a harmonic/spectrum analyser. To accurately measure the useful level of voltage or current in a non-sinusoidal AC supply, it is necessary to use true rms (root-mean-square) indicating instruments.

The harmonic content of the AC input to a synchroconverter also has components that are related to the motor operating frequency. The DC link reactor coil reduces the ripple in the link current so that the effect on the AC supply side is reduced.

The total heating effect of distorted (non-sinusoidal) current waveform is calculated from the rms sum of all harmonics including the fundamental (or 1^{st} harmonic), eg total rms value is:

$I = \sqrt{I_1^2 + I_5^2 + I_{11}^2 + I_{17}^2}$ for a waveform with three significant harmonics.

The % total harmonic distortion (THD) is found from the ratio of the sum of rms harmonics to the rms value of the fundamental.

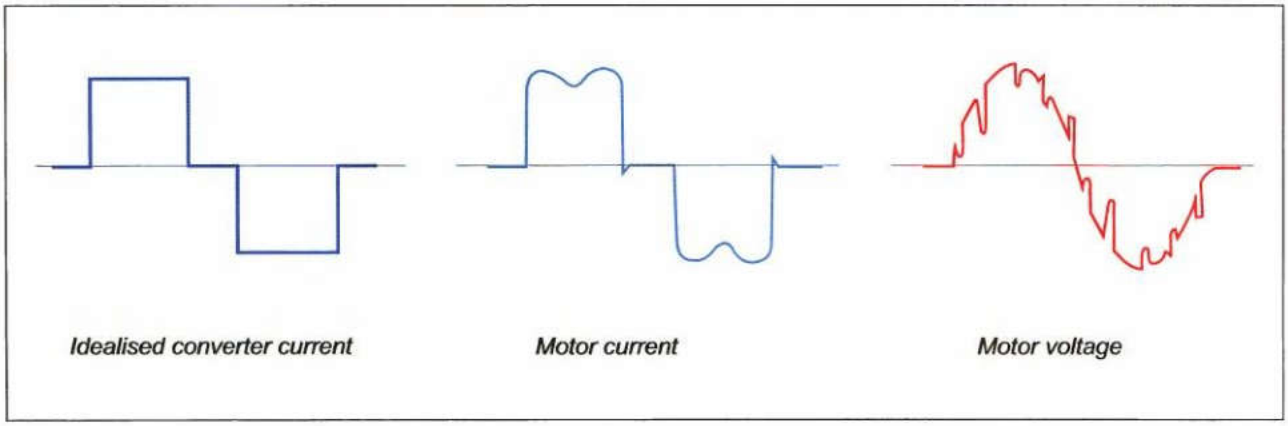


Figure 8.20 - Waveforms for synchrodrive converter

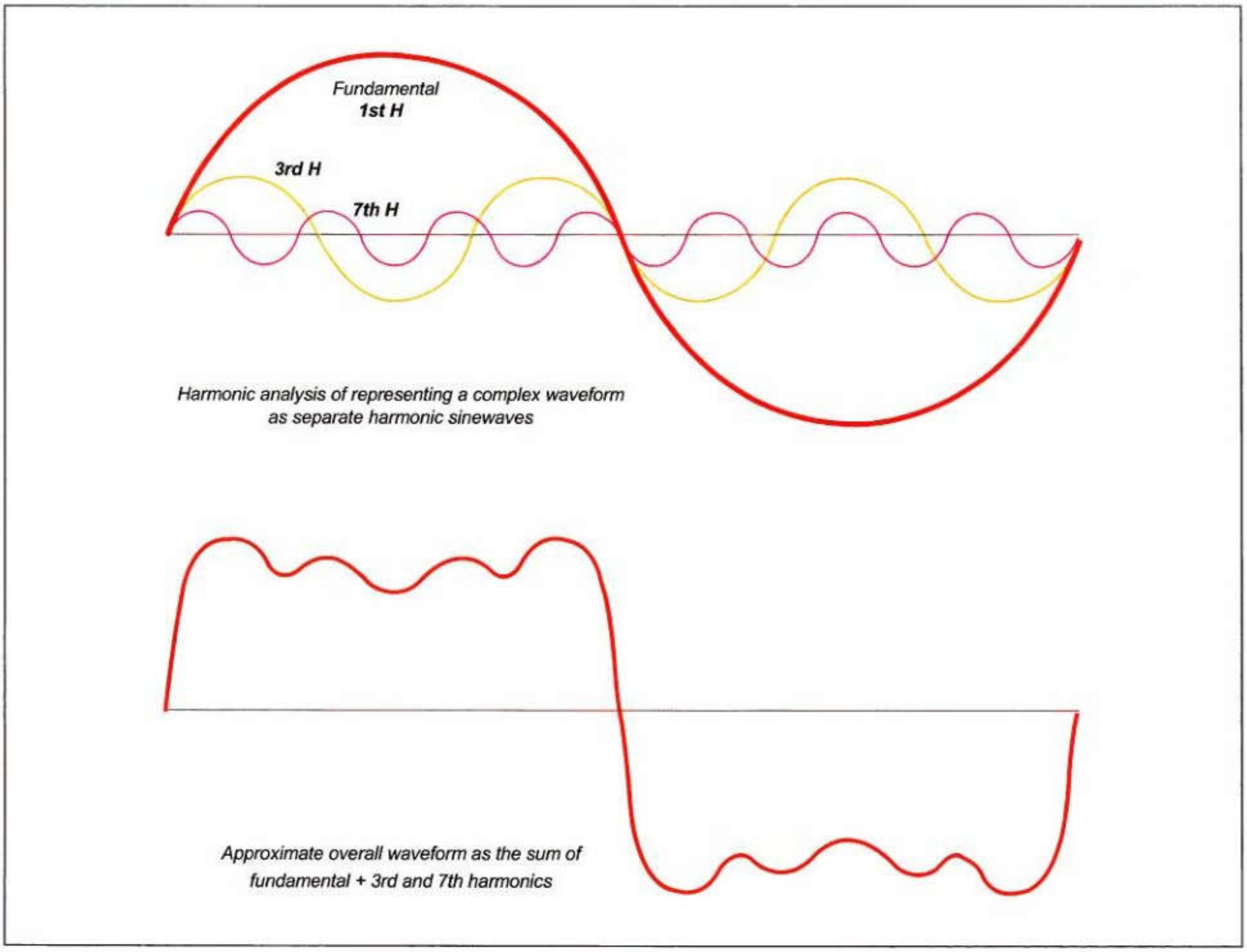


Figure 8.21 - Harmonic analysis of waveforms

QUESTION

A distorted 440 V, 60 Hz voltage waveform is found to include harmonics of:
20% 5^{th}; 9% 11^{th}; and 6% 17^{th}.

Determine the rms size of each harmonic voltage and the overall THD.

ANSWER

The 1^{st} harmonic rms level is 440 V.
The 5^{th} harmonic is 20% of 440 = **88 V**
Similarly, the 11^{th} harmonic is 40 V and the 17^{th} harmonic is 26 V.
The overall rms value of the three harmonics is

$$V_H = \sqrt{88^2 + 40^2 + 26^2} = 100 \text{ V}$$

So the THD = 100/440 = 0.227 per unit or **22.7%**

Most ship Classification Societies demand that the THD of the mains voltage is less than 10%, but in practice this is usually less than 5%.

To minimise the size of voltage distortion, it is necessary to connect filters that are tuned to the troublesome harmonics. The filters are combination sets of inductance (L) and capacitance (C), each resonantly tuned to a particular frequency in a series/parallel circuit. Additionally, some resistance (R) is included to act as a harmonic current limiting (damping) effect.

The simplest way to view the overall system is to consider that the converter injects harmonics while the filter absorbs them. Filtering is not perfect over the variable frequency range, so while the harmonic problem is not completely solved, it is minimised.

Practical harmonic installations in power systems are physically large and will create power losses and heat in the components.

A cycloconverter drive employs complex thyristor switching to create a variable low frequency output. The associated harmonics range is wide, variable and difficult to predict, so static filtering is difficult. With large cycloconverter drives (eg on a cruise ship), it is usual to employ a pair of motor generator sets (instead of transformers) between the 6.6 kV and 440 V switchboards. This arrangement provides a clean (harmonic-free) supply that does not transmit HV voltage variations to the LV side due to the rotational mechanical inertia of the M-G sets.

Where clean LV supplies are essential (eg 230 V, 50 Hz and 110 V, 60 Hz for instrument power on ocean survey ships with DC converters), it is usual to provide separate diesel generator sets for that purpose. In this case, the main power system would probably not employ harmonic filters but is likely to use capacitive voltage surge suppression to minimise over-voltage spikes on the main busbar supply.

The general problem of interference (noise) in electrical systems is how to minimise it at source and/or limit its transmission into adjacent susceptible equipment to prevent circuit malfunction. (Consider the interference to TV reception caused by the nearby operation of an electric power tool or unsuppressed motor bike ignition.)

The coupling between source and reception devices can be inductive (magnetic), electric (capacitive) or conductive (directly through the conductors). All of this is the subject of electromagnetic compatibility or EMC, which is a complicated analysis due to the wide range of possibilities for interference coupling. Manufacturers of electrical/communication equipment have to test their designs to prove and declare acceptable levels of compatibility.

Harmonic filtering and circuit screening are two methods of limiting interference effects, but no single method can be perfect. The most important factor that compromises a screen performance is its coverage of the circuit.

Think of radiated noise as visible light. A light bulb that is enclosed in a full metal box with no holes or gaps in any of the seams ensures that no light escapes from the box. If any holes exist in the box for cable entry/exit or the box seams are not perfect then light energy will escape. The amount of energy that can escape depends on the maximum linear dimension (L) of any aperture and the wavelength (λ) of the radiation (which is the principle used in microwave oven doors where visible light, which has a short wavelength, can pass through the door but microwaves, with a longer wavelength, cannot). Apertures can occur in door fittings, gaskets, ventilation holes, spaces for instruments, seams on boxes, cable entry and exit points, etc.

An important issue for interference is the coverage of screened and armoured cables, which is often far from ideal and allows leakage of radiation from the effective apertures caused by the braid knitting, and by the connection at either end of the screen/ armour. The more expensive screened/armoured cables have a better coverage and are preferred, but the effect can be negated by poor screen/ armour termination.

8.8 Propulsion Auxiliaries and Protection

The electric propulsion motor and its shaft bearings, converters, control regulators, transformers, reactor coils and harmonic filters all generate heat that must be continually removed by auxiliary cooling services. An overtemperature condition must be managed by load limitation or disconnection.

High current electrical components are generally cooled by forced air or by forced air/ water circulation. In a large propulsion motor, see Figure 8.22, an internal shaft-mounted fan circulates air through the rotor and stator spaces. This air is forced by electric fans to flow through a freshwater cooler, usually mounted on top of the machine, which removes the heat into the main cooling system. The motor enclosure will be typically rated as IP56 up to the shaft line, and IP44 above.

Stator winding, cooling air and water temperatures are monitored for display in the ECR. It is essential that general and hot spot temperature limits are not exceeded.

QUESTION

Which major feature of an electrical machine is principally degraded by overtemperature?

ANSWER

The insulation around the stator and rotor windings. Large HV machines are generally insulated with class F materials but will be normally operated well below this limit.

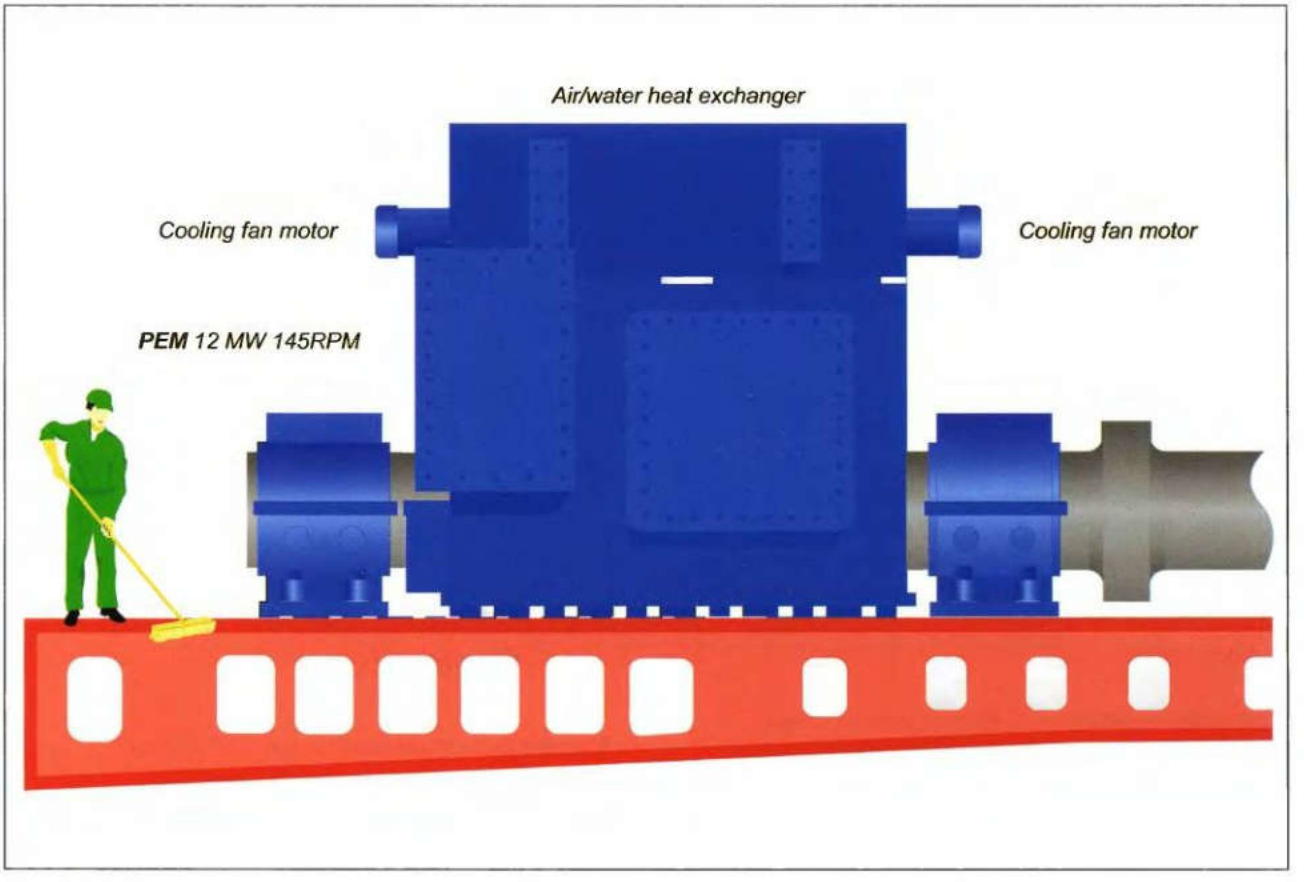


Figure 8.22 - Propulsion motor construction outline

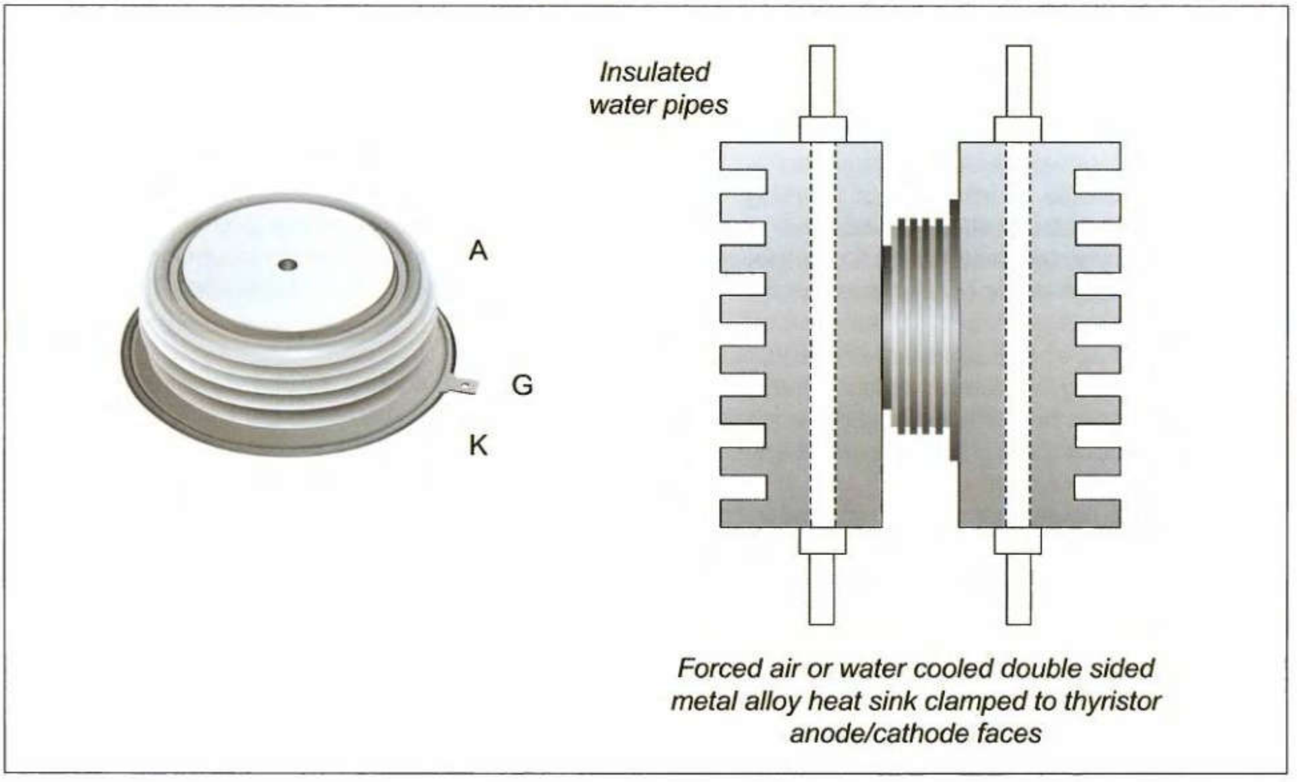


Figure 8.23 - Thyristor cooling arrangements

Large motors and generators have internal electric heaters that are activated when the machine is disconnected. The requirement is to raise the internal temperature to about 3°C above ambient, which will prevent condensation settling on the motor insulation. Typically, an anti-condensation heater rated at about 4 kW at 220 V would be fitted in a large HV machine.

Semiconductor components are particularly sensitive to temperature. In particular, the temperature of large current switching thyristors in the converters must be carefully managed. A perfect closed switch has no voltage drop across it so its power loss is zero when conducting. A thyristor, however, develops a small voltage drop (typically up to 2 V) when conducting its current. For a thyristor carrying an average current of, say, 2000 A, its power loss could be up to 4000 W, which would rapidly destroy the device unless the internal heat is efficiently removed.

Figure 8.23 shows how large power thyristors are clamped between large area metal heat sinks that conduct the internal heat away from the device. The heat sink is itself cooled by clean and dry forced air that is circulated through the converter cubicle, air filters and an air/water heat exchanger. A more effective method is to pump demineralised fresh water directly through the thyristor heat sinks and then circulate it through an external water/water heat exchanger.

QUESTION

The water used for heat sink cooling must be of exceptionally high purity. Why?

ANSWER

The metal alloy heat sinks form the electrical connections to anode and cathode so are live and at a high voltage level. Insulated, plastic piping is used and the electrical resistance of the water must be extremely high to avoid accidentally connecting the adjacent thyristors via the cooling medium.

The instrument used to measure the conductivity is similar to that used in a salinometer. Conductivity is measured in the units of micro-Siemen (μS) with acceptable values of less than 5 μS for thyristor cooling duty. If the set conductivity limit is exceeded, the test instrument will alarm and trip conditions, depending on the severity of the fault.

Protection of electrical power components requires that they are operated within their normal current, voltage and temperature ratings. A special case arises for the protection of large semiconductors, eg thyristors, which can be destroyed by a fast rate of change of voltage and current caused by rapid switching. Figure 8.24 shows thyristor protection.

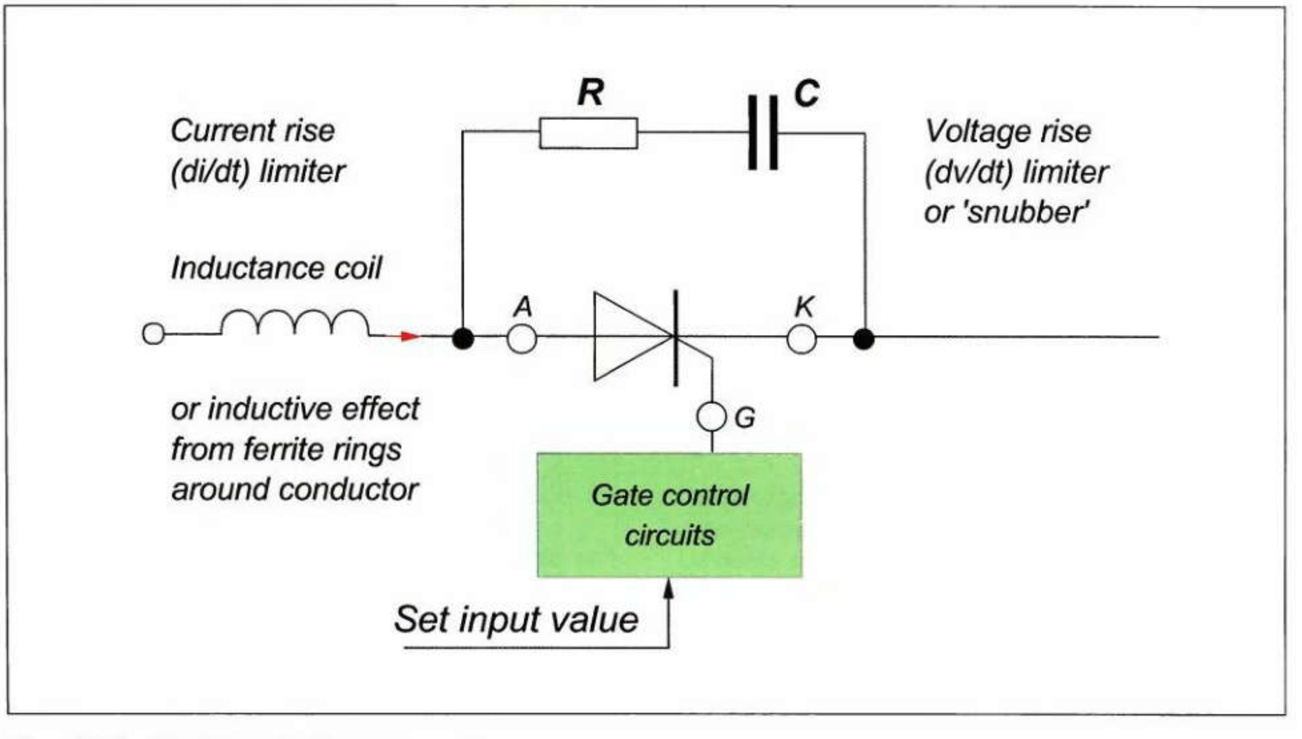


Figure 8.24 - Thyristor protection components

To suppress a rapid overvoltage rise (dv/dt) across a thyristor, an R-C snubber circuit is used. Its action is based on the fact that voltage cannot change instantaneously across a capacitor. The series resistor limits the corresponding current surge through the capacitor while it is limiting the voltage across the thyristor. Significant heat will be produced by the resistor which, in some applications, is directly cooled by a water jacket.

An in-line inductive effect will limit the rate of change of current (di/dt) through the thyristor. Special fast-acting line fuses may be used as backup overcurrent protection for the thyristors.

Circuit protection for the electric propulsion units (including excitation and harmonic filters) principally employs coordinated protective relays that monitor current, voltage, earth leakage and temperature. See Chapter 2 for protective relay functions and operation.

The settings of relay parameter level (overcurrent, undervoltage, etc) and their tripping times are critical to the circuit protection under fault conditions. Such settings have been very carefully matched to the circuit and its components. Confirmation testing of protective relays requires calibrated current and voltage injection, which is generally regarded as a specialist task for an outside contractor. Testing is normally performed during a major survey during a dry-docking period.

8.9 High Voltage on Ships

Ships with a large electrical power demand will require an HV installation. The design benefits relate to the simple Ohm's Law relationship that current size (for a given power) is reduced as the voltage is increased. Working at high voltage significantly reduces the relative overall size and weight of electrical power equipment. HV levels of 3.3 kV, 6.6 kV and 11 kV are regularly employed ashore for regional power distribution and industrial motor drives.

The main disadvantage perceived by the user/maintainer, when working in an HV installation, is the very necessary adherence to stringent safety procedures.

In the ship's power network shown in Figure 8.25, all of the equipment indicated above the dashed line is considered as HV. For the purposes of safety, this includes the LV field system for a propulsion motor as it is an integrated part of the overall HV equipment. From the HV generators, the network supplies HV motors (for propulsion, side thrusters and air conditioning compressors) and the step-down power transformers, which feed the 440 V switchboard. Further distribution links are made to interconnect with the emergency switchboard.

HV Circuit Breakers and Contactors

The main difference between an HV and an LV system is at the HV main switchboard. For HV, the circuit breaker types may be air break, oil break, gas break using SF6 (sulphur hexafluoride) or vacuum break. Of these types, the most popular and reliable are the vacuum interrupters, which may also be used as contactors in HV motor starters (see Figures 8.25, 3.20 and 3.21).

Each phase of a vacuum circuit breaker or contactor consists of a fixed and moving contact within a sealed, evacuated envelope of borosilicate glass.

When an alternating current is interrupted by the separating contacts, an arc is formed by a metal vapour from the material on the contact surfaces and this continues to flow until a current zero is approached in the AC waveform. At this instant, the arc is replaced by a region of high dielectric strength that is capable of withstanding a high recovery voltage. Most of the metal vapour condenses back on to the contacts and is available for subsequent arcing. A small amount is deposited on the shield placed around the contacts, which protects the insulation of the enclosure. As the arcing period is very short (typically about 15 ms), the arc energy is very much lower than that in air break circuit breakers, so vacuum contacts suffer considerably less wear.

Because of its very short contact travel, a vacuum interrupter has the following advantages:

- Compact quiet unit
- minimum maintenance
- non-flammable and non-toxic.

The life of the unit is governed by contact erosion, but could be up to 20 years.

In the gas-type circuit breaker, the contacts are separated in an SF6 (sulphur hexafluoride) gas that is typically at a sealed pressure chamber at 500 kPa or 5 bar (when tested at 20°C).

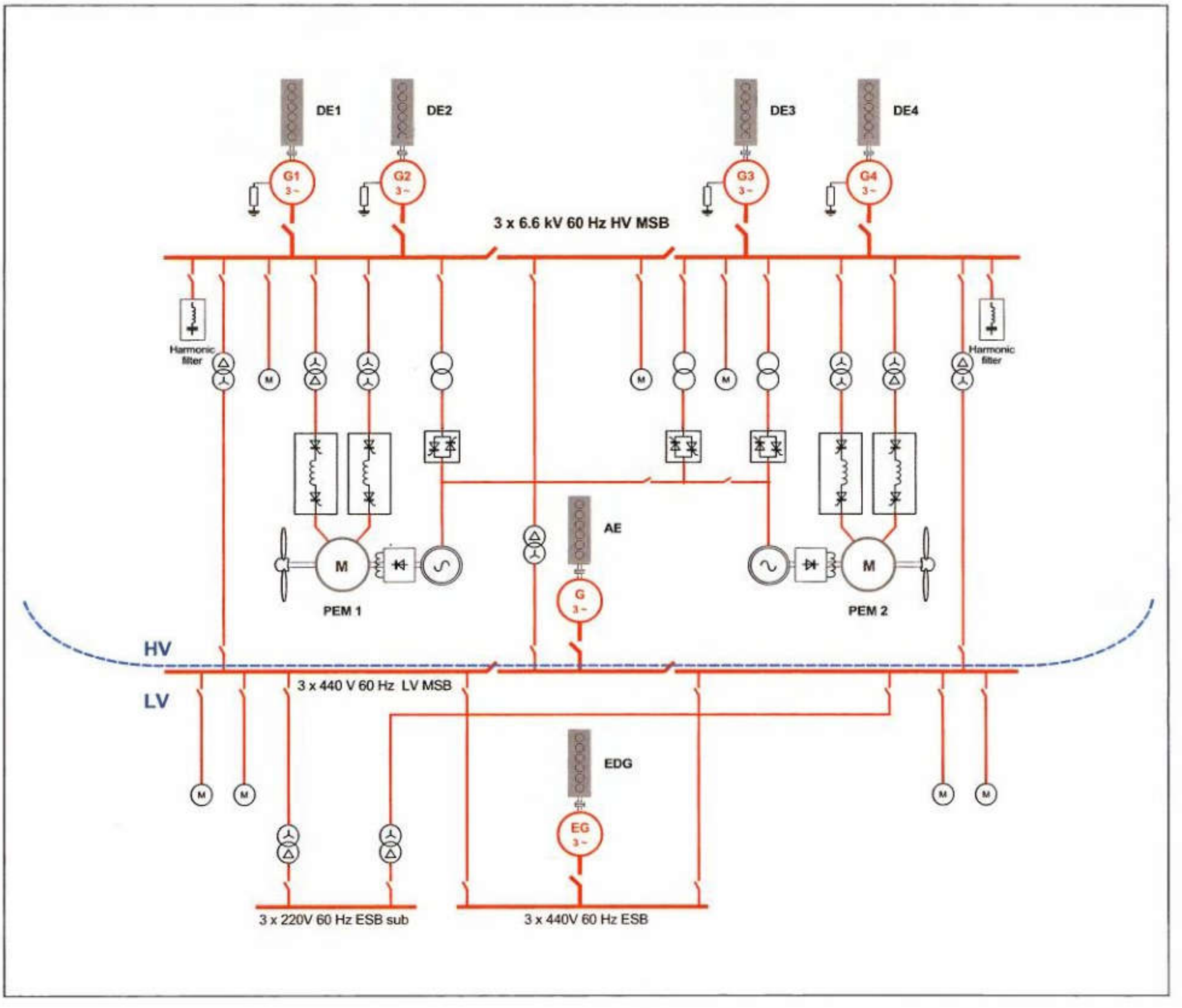


Figure 8.25 - HV/LV power supply system

QUESTION

Some HV systems have the neutral point of a generator earthed to the ship's hull via a neutral earthing resistor (NER). What is this connection for?

ANSWER

To minimise the size of earth fault current. A hard (zero resistance) earth fault causes a short-circuit across a generator phase winding, so the fault current is V_{PH}/R_{NER}.

For example, in a 6.6 kV system with a 200 Ω NER, ER,

$V_{PH} = 6600/\sqrt{3} = \mathbf{3810\ V}$

and the maximum E/F current is 3810/200 = **19 A**.

HV Insulation Requirements

The HV winding arrangements for generators, transformers and motors are similar to those for LV except for the need for better insulating materials.

The HV windings for transformers are generally insulated with an epoxy resin/powdered quartz compound. This is a non-hazardous material that is maintenance free, humidity resistant and tropicalised.

Conductor insulation for an HV cable requires a more complicated design than is necessary for an LV type. However, less copper area is required for HV conductors, which allows a significant saving in space and weight for an easier cable installation. Where the insulation is air (eg between bare metal live parts and earth within switchboards and in terminal boxes) greater clearance and creepage distances are necessary in HV equipment.

QUESTION

Would a 500 V megger test be suitable to determine the insulation integrity of a 6.6 kV motor?

ANSWER

No. It would give a rough guide to the IR value but at 500 V, the tester is not properly stressing the insulation. For 6.6 kV equipment, a 5000 V IR tester is required.

8.10 High Voltage Safety

Making personal contact with any electric voltage is potentially dangerous. At high voltage (>1000 V) levels, the electric shock potential is lethal. Body resistance decreases with increased voltage level, which enhances the current flow. Remember that an electric shock current as low as 15 mA can be fatal.

Figure 8.26 - HV warning notice

The risk to people working in HV areas is greatly minimised by the diligent application of company, industry, national and international safety guidelines, regulations and procedures. Personnel who are required to routinely test and maintain HV equipment should be trained in the necessary practical safety procedures and certified as qualified for this duty.

The 'Code of Safe Working Practices for Merchant Seamen (COSWP)', 2010, requires that work on HV equipment should only be carried out by competent or authorised persons, which it defines as:

*"**Authorised Person** - An Authorised Person is appropriately trained and appointed in writing by the Superintendent/Electrical Engineer to carry out work as permitted by these Rules.*

***Competent Person** - A Competent Person is appropriately trained and has sufficient technical knowledge or experience to enable him to avoid danger. It is the duty of the Authorised Person issuing a permit to work covered by these Rules to satisfy himself that persons are competent to carry out the work involved."*

Appropriate, approved and certified safety clothing, footwear, eye protection and a hard hat should be used where danger may arise from arcs, hot surfaces and high voltage, etc.

No work should be carried out on high voltage installations or equipment unless that equipment is:

"(a) Dead

(b) Isolated and all practicable steps have been taken to lock off live conductors, voltage transformers (except where the connections are bolted) and dead conductors that may become live.

(c) Earthed at all points of disconnection of High Voltage supply and caution notices attached in English and any other working language of the vessel.

(d) Released for work by the issue of a Permit to Work or a Sanction for Test.

(e) The Competent Person designated to carry out the work fully understands the nature and scope of the work to be carried out and has witnessed a demonstration that the equipment/installation is dead at the point of work".

COSWP, 2010

The access to HV switchboards and equipment must be strictly controlled by using a permit to work scheme (PTW) and isolation procedures together with live line tests and earthing down before any work is started. COSWP requires that

"A Limitation of Access instruction should be used to give written instructions defining the limits of work to be carried out in the vicinity of but NOT on High Voltage Equipment/ Installations."

The electrical permit requirements and procedures are similar to permits used to control access in any hot work situation, eg welding, cutting, burning, etc, in a potentially hazardous area.

All work to be carried out on HV equipment is subject to a PTW.

Permit to work (PTW)

The format of a permit will vary for different companies and organisations. COSWP Chapter 16 provides examples of PTWs for general electric work and for HV electrical work. These are included in Appendix 1 of this book.

Before work is commenced on HV equipment, a PTW must be issued. This permit is usually the last stage of a planned maintenance task that has been discussed, prepared and approved by the authorising officer to be carried out by the responsible person. The carbon-copied permit, signed by the responsible person, usually has at least five sections, with the first stating the work to be carried out. The next section is a risk assessment declaring where electrical isolation and earthing has been applied and where danger/caution notices have been displayed. The permit is signed as authorised by the Electrotechnical Officer (ETO) or Chief Engineer. In the third section, the person responsible for the work (as named in section one) signs to declare that they are satisfied with the safety precautions and that the HV circuit has been isolated and earthed. Section four relates to the suspension or completion of the designated work. Finally, the last section cancels the permit by a signature from the authorising officer. A PTW is usually valid only for 24 hours.

Some marine and offshore companies will also require an associated 'electrical isolation certificate' to declare and record exactly where the circuit isolation and earthing has been applied before the PTW can be authorised. A 'sanction to test' safety certificate may also be required when an electrical test (eg an electrical insulation test) is to be applied. This is necessary as the circuit earth generally has to be removed during such testing. A copy of a sanction to test format from COSWP is also provided in Appendix 1.

Before earthing down the particular circuit or equipment declared in the PTW, it must be tested and proved dead after disconnection and isolation. This can only be carried out by using an approved live line tester as shown in Figure 8.27. The tester itself must be proven before and after such a test. This is checked by connecting the tester to a known HV source (supplied either as a separate battery-operated unit or included as an internal self test facility).

Two people, competent in treating electric shocks, should always be together when working on HV equipment.

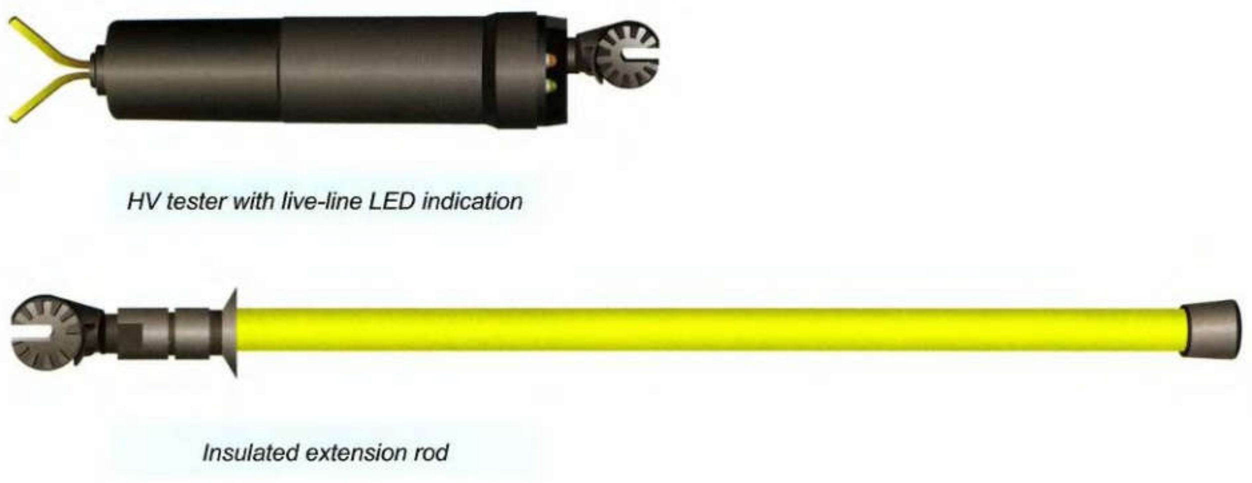


Figure 8.27 - HV live-line testing components

Earthing Down

Before work can be allowed to commence on HV equipment, it must be earthed to the hull and proved dead by an authorised person.

As an example, consider the earthing arrangements at an HV switchboard. Here, the earthing down method is of two types:

Circuit Earthing

After disconnection from the live supply, an incoming or outgoing feeder cable is connected by a manually-operated switch to connect all three conductors to earth. This action then releases a permissive key to allow the circuit breaker to be withdrawn to the TEST position. The circuit breaker cannot be re-inserted until the earth has been removed and the key restored to its normal position.

Busbar Earthing

When it is necessary to work on a section of the HV switchboard busbars, they must be isolated from all possible electrical sources. This will include generator incomers, section or bus-tie breakers and transformers (which could back-feed) on that busbar section. Earthing down is carried out at a bus-section breaker compartment after satisfying the permissive key exchanges. In some installations, the application of a busbar earth is by a special earthing circuit breaker, which is temporarily inserted into the switchboard solely for the busbar earthing duty.

For extra confidence and operator safety, additional earthing can be connected locally to the work task with approved portable earthing straps and an insulated extension tool, eg at the terminals of an HV motor, as shown in Figure 8.28.

Remember to always connect the common wire to earth first before connecting the other wires to the three-phase connections. When removing the earthing straps, always remove the earth connection last.

COSWP provides the following advice when earthing:

> *"Circuit Main Earths shall be applied and removed only by an Authorised Person, or by a person Competent to do so in his presence and to his instructions.*
>
> *When High Voltage Equipment/Installations have been made dead and Isolated, the Conductors to be Earthed shall be proved Dead if practicable using an Approved potential indicator. The potential indicator should be in date for calibration and be tested immediately before and after use, to prove it is in good working order.*
>
> *Where practicable Circuit Main Earths shall be applied through a circuit breaker or earthing switches.*
>
> *Before closing to earth, the trip features shall be rendered inoperative unless this is impracticable. After closing, the circuit breaker shall be locked in the earth position and the trip features rendered inoperative with a caution notice attached.*
>
> *Additional Earths may be applied at the point of work after the issue of a Permit to Work by the Competent Person in charge of the work.*
>
> *Circuit Main Earths/Additional Earths may also be removed/replaced at the point of work after the issue of a Sanction for Test by the Authorised person conducting the test.*
>
> *A Circuit Main Earth applied at the point of work may be removed and replaced one phase at a time to facilitate the work provided this instruction is recorded on the Permit to Work. If this is the only Circuit Main Earth connected to the apparatus, then a person Authorised to issue Permits to Work shall remain at the point of work and be responsible for the safety of all those engaged in the work whilst the Circuit Main Earth is removed. No other simultaneous work shall be permitted on any part of the circuit during the validity of this Permit to Work."*

COSWP Section 22.15.11

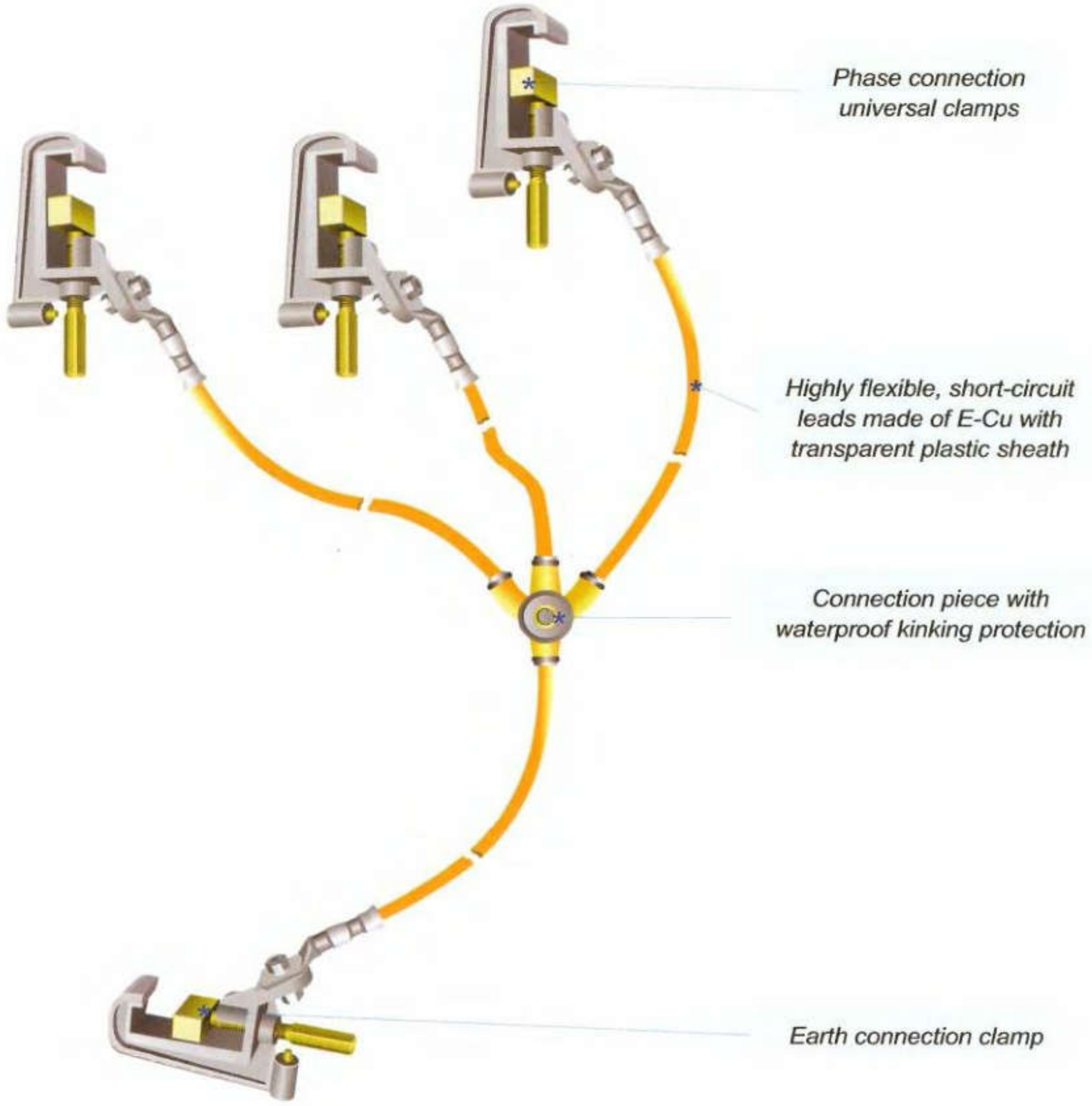


Figure 8.28 - Portable earthing connectors

QUESTION

Why is earthing down considered essential during HV maintenance?

ANSWER

So that the worker can be assured that the equipment (and himself) cannot experience any accidentally applied voltage because the earth connection bonds the circuit to earth (zero volts).

8.11 High Voltage Equipment Testing

The HV (eg 6.6 kV) installation covers the generation, main supply cables, switchgear, transformers, electric propulsion (if fitted) and a few large motors, eg for side-thrusters and air conditioning compressors. For all electrical equipment, the key indicator to its safety and general condition is its insulation resistance (IR) and this is particularly so for HV apparatus. The IR must be tested periodically between phases and between phases and earth. HV equipment that is well designed, maintained and operated within its power and temperature ratings should have a useful insulation life of 20 years.

An IR test is applied with a high DC voltage that applies a reasonable stress to the dielectric material (insulation). For 6.6 kV rated equipment, a periodic 5000 V DC insulation resistance (megger) test is recommended. The IR test should be applied for one minute and temperature corrected to a standard of 40°C. The minimum IR value is usually recommended as (kV + 1) MΩ, where kV is the equipment voltage rating, eg 7.6 MΩ would be an acceptable IR value for a 6.6 kV machine. For machines with healthy insulation, an IR test result may indicate a value up to 100 times greater than the recommended minimum.

A more involved IR test (the polarisation index or PI) is used when the insulation value may be suspect or recorded during an annual survey. The PI value is the ratio of the IR result after 10 minutes of testing (R_{10}) to the value recorded after one minute (R_1):

$$PI = R_{10}/R_1$$

For class F insulation materials, the recommended PI value is 2. To apply a PI test over a 10 minute period requires a special IR tester that has a motor-driven generator or an electronic converter powered from a local 220 V AC supply.

The condition of HV insulation is governed by factors such as temperature, humidity, surface condition and operating voltage level. Be guided by the manufacturer's recommendations when testing and maintaining HV insulation.

PI was developed to make interpretation less sensitive to temperature. PI is the ratio of two IR at two different times. The temperature of the winding does not rise during the 10 minute test period so it is fair to assume that both R_{10} and R_1 are measured at the same winding temperature. The temperature correction factor will then be the same for both cases and will be cancelled during the calculation of PI. Therefore, PI is relatively insensitive to temperature.

Before applying an IR test to HV equipment, its power supply must be switched off, isolated, confirmed dead by an approved live line tester and then earthed for complete safety in accordance with the current PTW regulations.

The correct procedure is to connect the IR tester to the circuit under test with the safety earth connection ON. The safety earth may be applied through a switch connection at the supply circuit breaker or by a temporary earth connection local to the test point. This is to ensure that the operator never touches an unearthed conductor. With the IR tester connected, the safety earth is disconnected (using an insulated extension tool for the temporary earth). The IR test is then applied and recorded. The safety earth must be reconnected before the IR tester is disconnected. This safety routine must be applied for each separate IR test.

Large currents flowing through machine windings, cables, busbars and main circuit breaker contacts will cause a temperature rise due to I^2R resistive heating. Where overheating is suspected, at a bolted busbar joint in the main switchboard for example, the local continuity resistance may be measured and checked against the manufacturer's recommendations or compared with similar equipment that is known to be satisfactory. A normal ohmmeter is not suitable as it will only drive a few mA through the test circuit. A special low resistance tester, or micro-ohmmeter, (traditionally called a ducter) must be used. It drives a calibrated current (usually I = 10 A) through the circuit while measuring the volt-drop (V) across the circuit. The meter calculates R from V/I and displays the test result. For a healthy busbar joint, a continuity of a few mΩ would be expected.

Normally, the safe testing of HV equipment requires that it is disconnected from its power supply. Unfortunately, it is difficult and unsafe to closely observe the on load operation of internal components within HV enclosures. This is partly resolved by temperature measurement with an infrared camera recording from a safe distance. The camera is used to scan an area and the recorded infrared image is then processed by a computer programme to display hot spots and a thermal profile across the equipment. To examine internal components, eg busbar joints, a camera recording can be made immediately after the equipment has been switched off and isolated in accordance with a PTW safety procedure. Alternatively, some essential equipment, eg a main switchboard, can be monitored on line using specially fitted and approved enclosure windows suitable for infrared testing. These windows are small apertures with a permanently fixed steel mesh through which the camera can view the internal temperature from a safe position. An outer steel plate fixed over the window mesh maintains the overall enclosure performance during normal operation.

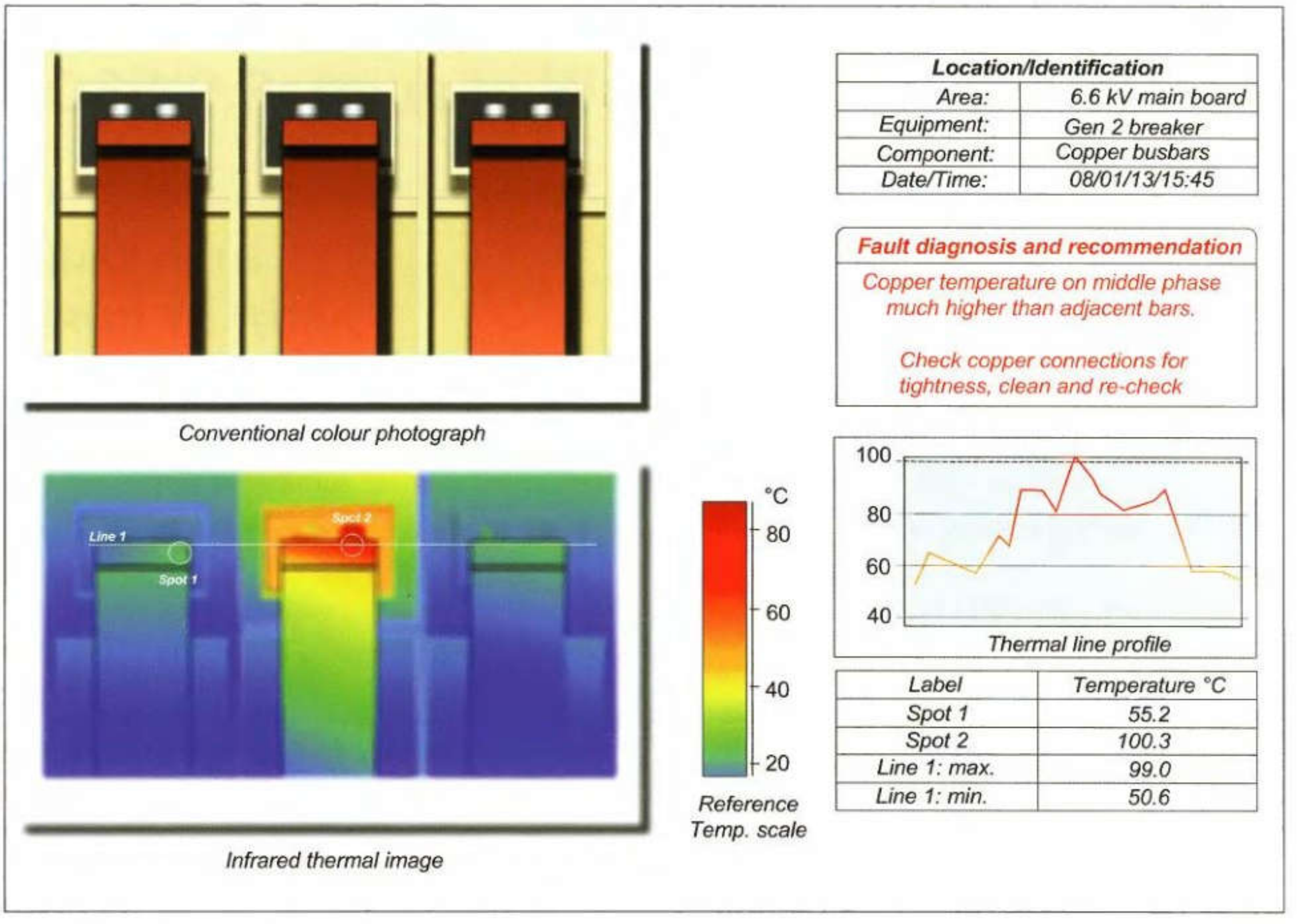


Figure 8.29 - Infrared image testing

A conventional photograph of the equipment is taken simultaneously to match the infrared image and both are used as part of a test report. Such testing is usually performed by a specialist contractor who will prepare the test report and propose recommendation/repair advice to the ship operator.

Figure 8.29 shows results from an infrared camera test on a busbar connection. In this particular test, the camera recorded hot spot temperatures up to 100°C and the report recommended that the copper connection was checked for tightness as it was running very hot compared to that on the neighbouring copper work.

To test the insulating integrity of an HV vacuum type circuit breaker requires a special high voltage impulse test. The tester produces a short duration voltage pulse, of typically 10 kV for a 6.6 kV circuit, that is connected across the open breaker contacts. Any weakness in the insulating strength of the vacuum in the interrupter chamber will be detected as a current flow and the tester will display the condition as a pass or fail.

Gas (SF6) HV circuit breakers rely on the quality and pressure of the gas acting as the insulation between the contacts. A falling gas pressure can be arranged to initiate an alarm from pressure switches fitted to each switching chamber. Normal gas pressures are typically 500 kPa or 5 bar.

Overall circuit protection of HV equipment is supervised by coordinated protective relays. These must be periodically tested to confirm their level settings (for current, voltage, frequency, etc) and their tripping times. This requires the injection of calibrated values of current and voltage into the protective relays, which is usually performed by a specialist contractor during a main ship survey while in dry-dock.

Appendix 1
COSWP Permits to Work

ANNEX 16.1.6

PERMIT-TO-WORK – GENERAL ELECTRICAL (UNDER 1000 VOLTS)

Note (i): The Authorising Officer should indicate the sections applicable by ticks in the lefthand boxes next to headings, deleting any subheading not applicable.

Note (ii): The Authorising Officer should insert the appropriate details when the Sections for Other Work or Additional precautions are used.

Note (iii): The Authorised Person should tick each applicable righthand box as they make their check.

Note (iv): This Permit-to-Work contains 6 sections.

SECTION A – Scope of Work

Location (designation of space) ....

....

Plant Apparatus/Identification
(designation of machinery/equipment) ....

....

....

Work to be done (description) ....

....

....

Permit issued to (name of person carrying out work or in charge of the work party) ....

....

Section B – Check List/Isolation Data

Has a risk assessment of the proposed work been carried out?

The above apparatus is dead and has been isolated from the system at the following points
(Description) ....

....

....

Safety Locks (Detail location fitted and identify lock set) ....

....

....

Additional Precautions to avoid danger have been taken by (Description) ....

....

....

Caution/Danger notices have been applied at all points of isolation, and Safety Signs appropriately positioned.

TREAT ALL OTHER APPARATUS AND AREAS AS DANGEROUS

....

....

....

....

....

....

SECTION C – Authorising of permit

Period of validity of permit (should not exceed 24 hours) .... hours. I am satisfied that all precautions have been taken and that safety arrangements will be maintained for the duration of the work.

Authorising person

(Name)... (Signature)..

(Time) .... (Date)...

SECTION D – Receipt of Permit

I accept responsibility for carrying out the work on the apparatus detailed on this permit to work and no attempt will be made by me or people under my charge to work on any other apparatus or in any other area.

I am satisfied that all precautions have been taken and that safety arrangements will be maintained for the duration of the work.

Safety Key No .... Received*/Applied*

Competent person

(Name)... (Signature) ....

(Time) .... (Date)...

Note: After signing the receipt, this permit to work should be retained by the person in charge at the place where the work is being carried out until work is complete and the clearance section signed

---

SECTION E – Clearance of Permit

The work for which this permit to work was issued is now suspended*/completed* and all people under my charge have been withdrawn and warned that it is no longer safe to work on the apparatus detailed in this permit to work.

All work equipment, tools, test instruments etc have been removed.

Competent person

(Name).. (Signature) ....

(Time) .... (Date)..

Safety Key No .... Received*/Applied*

SECTION F – Cancellation of Permit

This Permit to work is cancelled.

Authorising Person

(Name).. (Signature)..

(Time) .... (Date)..

Safety Key No .... Received*/Applied*

* Delete words not applicable and where appropriate state:
The work is complete*/incomplete* as follows: (description)

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ANNEX 16.1.7

PERMIT-TO-WORK – ELECTRICAL HIGH VOLTAGE (OVER 1000 VOLTS)

Note (i): The Authorising Officer should indicate the sections applicable by ticks in the lefthand boxes next to headings, deleting any subheading not applicable.

Note (ii): The Authorising Officer should insert the appropriate details when the Sections for Other Work or Additional precautions are used.

Note (iii): The Authorised Person should tick each applicable righthand box as they make their check.

Note (iv): This Permit-to-Work contains 6 sections.

SECTION A – Scope of Work

Location (designation of space) ....

....

Plant Apparatus/Identification
(designation of machinery/equipment) ....

....

....

Work to be done (description) ....

....

....

Permit issued to (name of person carrying out work or in charge of the work party) ....

....

Section B – Check List/Isolation Data

Has a risk assessment of the proposed work been carried out?

The above apparatus is dead and has been isolated from the system at the following points
(Description) ....

....

....

Circuit Main Earths have been applied to the equipment at the following points. (Description) ....

....

....

Safety Locks
(Detail location fitted and identify lock set) ....

....

Additional Precautions to avoid danger have been taken by
(Description) ....

....

Caution/Danger notices have been applied at all points of isolation, and Safety Signs appropriately positioned.

TREAT ALL OTHER APPARATUS AND AREAS AS DANGEROUS

....

....

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....

SECTION C – Authorising of permit

Period of validity of permit (should not exceed 24 hours) .... hours. I hereby declare that the above equipment is dead and isolated from all live conductors.

Authorising person

(Name).. (Signature) ....

(Time) .... (Date)...

SECTION D – Receipt of Permit

I accept responsibility for carrying out the work on the apparatus detailed on this permit to work and no attempt will be made by me or people under my charge to work on any other apparatus or in any other area. I am satisfied that all precautions have been taken and that safety arrangements will be maintained for the duration of the work.

Safety Key No .... Received*/Applied*

Competent person

(Name).. (Signature)..

(Time) .... (Date)...

Note: After signing the receipt, this permit to work should be retained by the person in charge at the place where the work is being carried out until work is complete and the clearance section signed

SECTION E – Clearance of Permit

The work for which this permit to work was issued is now suspended*/completed* and all people under my charge have been withdrawn and warned that it is no longer safe to work on the apparatus detailed in this permit to work.

All work equipment, tools, test instruments etc have been removed.

Competent person

(Name).. (Signature) ....

(Time) .... (Date)...

Safety Key No .... Received*/Applied*

SECTION F – Cancellation of Permit

This Permit to work is cancelled.

Authorising Person

(Name).. (Signature)...

(Time) .... (Date)...

Safety Key No .... Received*/Applied*

* Delete words not applicable and where appropriate state:
The work is complete*/incomplete* as follows: (description)

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ANNEX 16.2.1

SANCTION-TO-TEST – ELECTRICAL HIGH VOLTAGE SYSTEMS (OVER 1000 VOLTS)

Note (i): The Authorising Officer should indicate the sections applicable by ticks in the left hand boxes next to headings, deleting any subheading not applicable.

Note (ii): The Authorising Officer should insert the appropriate details when the Sections for Other Work or Additional precautions are used.

Note (iii): The Authorised Person should tick each applicable righthand box as they make their check.

Note (iv): This Sanction-to-Test contains 6 sections.

SECTION A – Scope of Work

Location (designation of space) ....

....

Plant Apparatus/Identification
(designation of machinery/equipment) ....

....

....

Work to be done (description) ....

....

....

Permit issued to (name of person carrying out work or in charge of the work party) ....

....

Section B – Check List/Isolation Data

Has a risk assessment of the proposed work been carried out?
The above apparatus is dead and has been isolated from the system at the following points
(Description) ....

....

....

Circuit Main Earths have been applied to the equipment at the following points.
(These Earths may be removed and replaced to your instructions)
(Description) ....

....

....

Safety Locks
(Detail location fitted and identify lock set) ....

....

Additional Precautions to avoid danger have been taken by
(Description) ....

....

Caution/Danger notices have been applied at all points of isolation, and Safety Signs appropriately positioned.

TREAT ALL OTHER APPARATUS AND AREAS AS DANGEROUS

....

....

....

....

....

SECTION C – Authorising of Sanction-to-Test

Period of validity of sanction-to-test (should not exceed 24 hours) .... hours. I hereby declare that the above equipment is dead and isolated from all live conductors and connected to earth.

Authorising person

(Name).. (Signature) ....

(Time) .... (Date)...

SECTION D – Receipt of Sanction-to-Test

I accept responsibility for carrying out the work on the apparatus detailed on this sanction-to-test and no attempt will be made by me or people under my charge to work on any other apparatus or in any other area. I am satisfied that all precautions have been taken and that safety arrangements will be maintained for the duration of the work.

Safety Key No .... Received*/Applied*

Competent person

(Name).. (Signature)..

(Time) .... (Date)...

Note: After signing the receipt, this sanction-to-test should be retained by the person in charge at the place where the work is being carried out until work is complete and the clearance section signed

SECTION E – Clearance of Sanction-to-Test

The work for which this sanction-to-test was issued is now suspended*/completed* and all people under my charge have been withdrawn and warned that it is no longer safe to work on the apparatus detailed in this permit to work.

All work equipment, tools, test instruments etc have been removed.

Competent person

(Name).. (Signature)..

(Time) .... (Date)...

Safety Key No .... Received*/Applied*

SECTION F – Cancellation of Sanction-to-Test

This Sanction-to-Test is cancelled.

Authorising Person

(Name).. (Signature)..

(Time) .... (Date)..

Safety Key No .... Received*/Applied*

* Delete words not applicable and where appropriate state:
The work is complete*/incomplete* as follows: (description)

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