12

Protective Relay Coordination

12.1 INTRODUCTION TO OVERCURRENT COORDINATION

Protective devices, usually relays or fuses, are installed at supply points in a power system to accurately detect and quantify a disruptive disturbance in the system. The variable most frequently used for detection is the supply line current, and in most situations this is detected through the use of current transformers. Occasionally direct acting devices are used e.g. fuses for voltages up to about 33,000 volts or magnetic elements in low voltage moulded-case circuit breakers (MCCBs).

For special purposes other variables such as voltage, active power, impedance, admittance and frequency are used.

Most onshore oil production, petrochemical, industrial and offshore platforms use radial power generation and distribution power systems. These systems will use several voltage levels depending upon the total power demand and the kW ratings of the largest individual consumers. The transition from one voltage to the next higher one is influenced mainly by the highest normal load current that can be handled by conventional circuit breakers, busbar systems within switchgear and power cables. The 'highest' current is typically about 4000 amperes. The maximum fault currents that can be experienced within a particular power system must also be carefully considered when choosing the operating voltages. (If in any doubt, then choose a higher voltage because plants are usually extended or modified, and as such their prospective fault currents tend to increase.)

Figure 12.1 shows a typical hierarchy of switchboards and voltages for a large plant which has its own gas-turbine power generators (not all the switchboards and individual consumers are shown). The hierarchy of switchboards, for example, SB-A, SB-B, SB-C and SB-D is a typical situation, and is one in which overcurrent coordination can occasionally be difficult to achieve for all operating considerations.

There are two basic operating cases to consider:-

a) Fully loaded power system with all the main generators running. (Usually one is off-line as a standby, but periodically this generator will need to be put on-line to relieve one of the others. Hence a major fault could occur during the changeover situation.)
b) Lightly loaded power system with only one generator running. This could be during the start-up of the production plant. The fault currents throughout the system will be at their lowest levels and this will tend to cause the fault clearance times to rise, and the coordination margins to increase.

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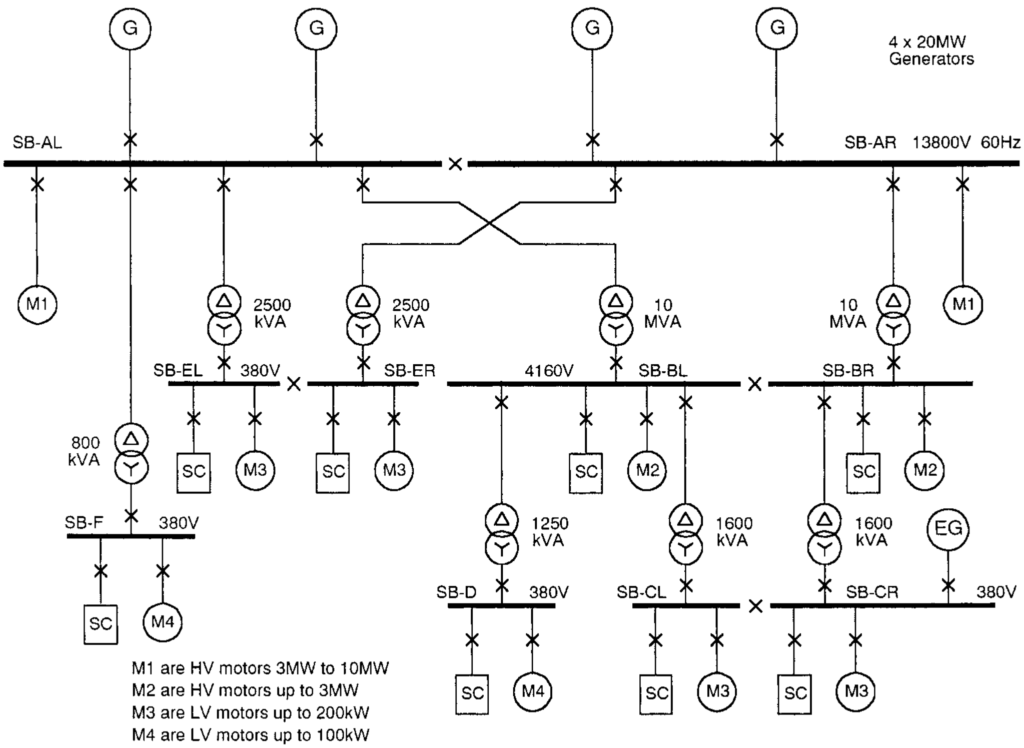

Figure 12.1 One-line diagram of an equivalent power system that has its own dedicated generators, showing the hierarchy of the switchboards.

The relay coordination is mainly based on the requirements imposed by case a) e.g. starting large motors direct-on-line, faults at switchboard busbars, faults at consumer terminal boxes. It is reasonable to assume that the plant will operate as in a) for 90% or more of its lifetime. However, the system must have satisfactory, not necessarily the best, coordination for start-up and light load operations as in case b). Operational restrictions at light load may assist the coordination calculations e.g. most large HV motors would not be running, hence their starting performances need not be considered, when switchboard feeder circuit breakers are being examined.

When all the overcurrent curves are plotted for the main generators, transformer feeders, large motors and downstream feeders, they tend to be located 'close together', and without much room for adjustment. This is made more difficult when there are:-

- A large number of small main generators e.g. 4, 6 or 8 as compared with 2 generators.
- The largest motors that are started direct-on-line at the main generator switchboard are large compared with the smallest generator e.g. 20% or larger.
- The largest motors that are started direct-on-line at the lower voltage switchboards are large compared with the rating of the transformers that feed the switchboard e.g. 20% or larger.
- The standing load at a switchboard is high (80% or more) compared with its feeder capacity. This is especially a problem at the main generator switchboard when b) applies, see sub-section 12.2.2.4.

- The large motors have long run-up times e.g. 10 to 20 seconds for high speed centrifugal gas compressors.

In this section the protective relays and their functions are described in a sequence that pertains to the protected equipment in a power system. The sequence begins with generators because these are usually the main source of power in the network. At the end of the sequence are the smaller power-rated equipment. The sequence is:

- Main generators.
- Emergency diesel generators.
- Feeder transformers.
- Feeder cables.
- Feeder overhead lines.
- Switchboard interconnectors.
- Switchboard busbar section circuit breakers.
- Large motors.
- Small motors.
- Static loads.

12.1.1 Relay Notation

There are two generally accepted methods of describing and notating relays and protective devices. The first and earliest system to be rationalised is that developed by the IEEE in its standard C37.2 in 1970, which has also been revised in 1991. Appendix C gives a comprehensive listing and description of each function. This method uses a simple numbering system of up to two digits, together with one or two suffixed letters, to identify the function of the device. Its simplicity is an attractive advantage and most relay and switchgear manufacturers are very familiar with the numbers.

The second system is based on the IEC60255 and its references. The symbols used are comprehensive but tend to suffer from poor clarity when photoreduced, as is often required with engineering drawings. The first method is regularly used in the oil industry and is preferred herein.

Appendix C herein gives the IEEE device numbers that are most commonly used, together with their descriptions that are typically used in the oil industry.

12.2 GENERATOR PROTECTION

12.2.1 Main Generators

For generators in the range of approximately 2 MW to 50 MW the following protection relays should be provided:-

- Overcurrent (51 V).
- Differential stator current (87).
- Field failure (40).
- Field winding earth fault (58).

- Reverse active power (32).
- Negative phase sequence (46).
- Stator earth fault current (51 G) and (64).
- Over terminal voltage, (59) Note 1.
- Under terminal voltage, (27) Note 1.
- Overfrequency, (81) Note 2.
- Underfrequency, (81) Note 2.
- Winding temperature (26).

Note 1: These can be combined in one voltage relay.

Note 2: These can be combined in one frequency relay.

A typical scheme that contains most of these relays is shown in Figure 12.2.

12.2.2 Overcurrent

12.2.2.1 Response of a generator to a major fault

When a major fault occurs externally from the generator but near to the generator stator terminals or near its switchgear, two reactions take place:-

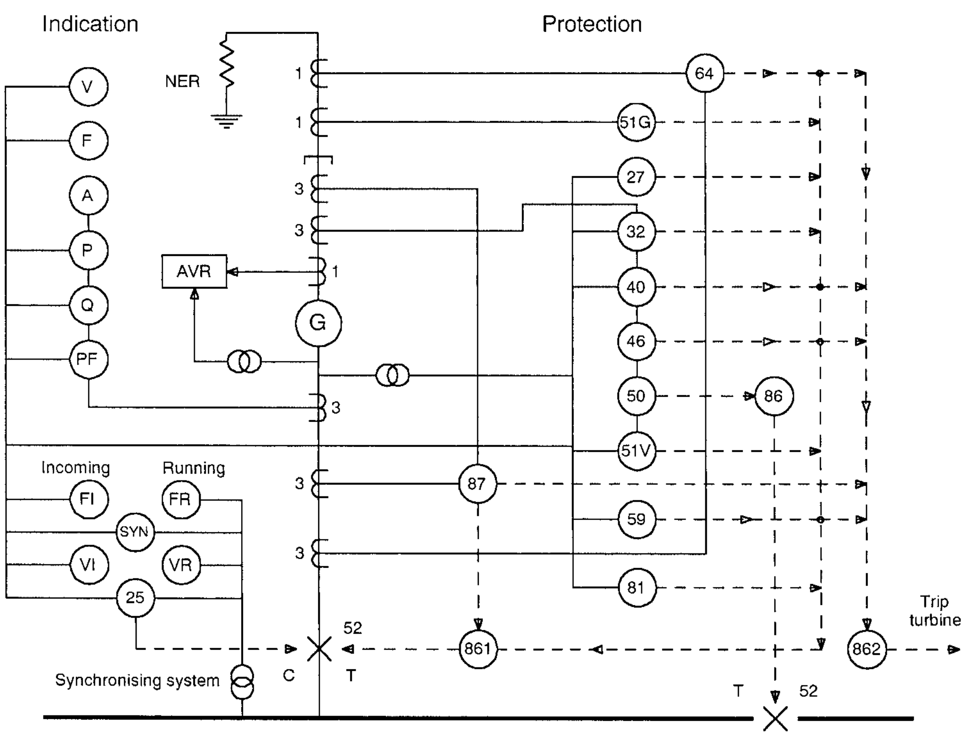

Figure 12.2 Protective devices for a high voltage generator.

a) The fault current supplied by the generator is initially high (approximately 5 to 8 times the full-load current) but decays within a few tens of cycles to a much lower value. This lower value is determined by the synchronous reactance and the maximum output current of the exciter. See Figure 12.3 which shows the stator current response to a full short circuit at its terminals. Two cases are shown, one with the AVR functioning, which is invariably the case, and the other with the excitation fixed at its pre-fault value which is a non-practical situation but emphasises the effect of the AVR. These responses are called the 'Generator Decrement Curves', and are required when relay coordination studies are being carried out, see Reference 8.

b) The terminal voltage of the generator falls to a value determined by the location and impedance of the fault circuit.

12.2.2.2 Overcurrent characteristic

The basic characteristic of the relay before it is modified by the voltage signal, as explained in sub-section 12.2.2.3, can be either a) definite time, b) inverse with a minimum time value, see Figure 12.5 or Figure 12.6 extremely inverse with a minimum time value.

12.2.2.3 Voltage restraint

A standard overcurrent relay does not have a characteristic that can give a fast enough response once the initial decay of a) above has taken place. To overcome this effect the change in terminal voltage

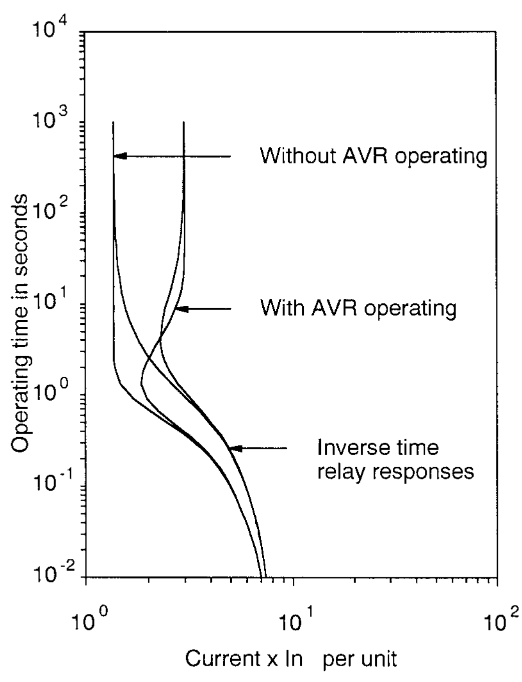

Figure 12.3 Decrement currents in a system that is fed by synchronous generators. The diagram shows the current responses where the generators are equipped with AVRs and without AVRs.

at the generator is used to measure the severity of the fault. The greater the fall in voltage the more severe is the fault. The measured voltage is used to modify the characteristic of the relay. Electronic relays use a function generator and a multiplying element to achieve the required characteristic. The voltage signal is used to automatically reduce the time setting, which is often called the 'Time Multiplier Setting'. There are several methods frequently used, two of which are:-

a) Two definite levels of voltage.

b) Continuously variable between two limiting values of voltage.

This type of relay is called a 'Voltage Restrained Overcurrent Relay' (51 V). It often has a definite minimum time limitation built into its design.

A typical multiplying function for the continuously acting voltage restraint is:-

$$K_v = \left(\frac{1.333 \times V - 6.667}{100}\right) \text{per unit}$$

For V in the range 20% to 80%, Figure 12.4 shows the voltage restraint function.

The 'unrestrained' operation of these relays is used as back-up overcurrent protection for downstream relays in case they fail to respond.

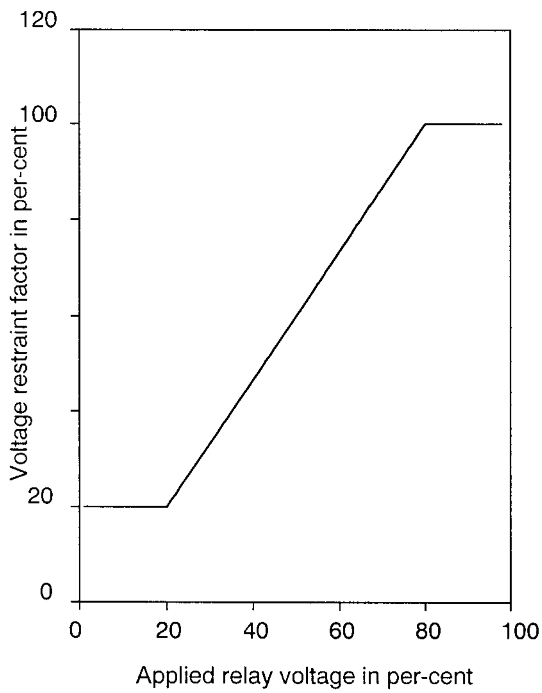

Figure 12.4 Voltage restraint characteristic for a 51 V relay.

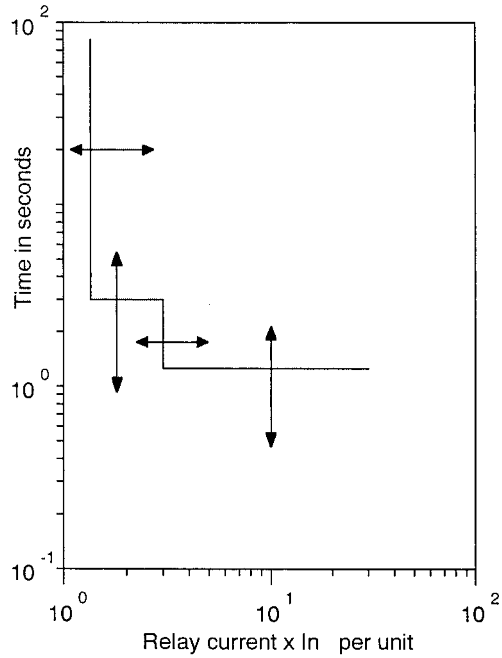

Figure 12.5 Definite time overcurrent relay with a two-stage characteristic.

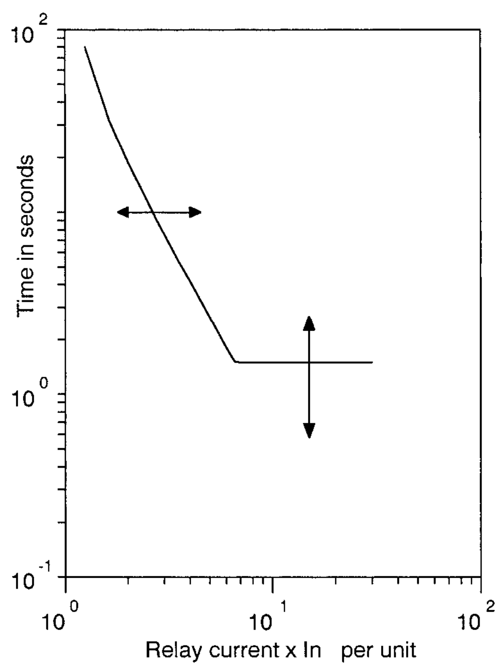

Figure 12.6 Inverse time overcurrent relay with a definite minimum time limit at high fault currents.

12.2.2.4 Influence of the load characteristics

Occasionally a power system may contain motors that have a normal continuous rating, that is large in comparison with any one of the main generators in the system. All the generators may not be of the same rating.

Direct-on-line starting of these large motors can cause several problems with the performance of the generator protection relays, for example:-

a) Voltage dip at the generator terminals during the first 100 milliseconds, or so, as the motor begins to run up to speed. This is caused by the high reactive current drawn by the motor, which remains nearly constant until the motor approaches its full-speed operation. Voltage dip can cause tripping of downstream switchgear if its control circuit supplies are taken from the AC power system e.g. switchgear voltage transformers. Prolonged voltage dip may occur if the generator excitation is not provided with sufficient ceiling voltage capability.
b) Overvoltage can occur at the end of the motor run-up period if the generator excitation has been forced to a high level. The sudden loss of the high reactive starting current will raise the generator terminal voltage significantly, which may take a second, or so, of time to recover. For high voltage systems this rise in voltage may be unacceptable for the insulation limits of equipment in the system e.g. motors, transformers, cables. This problem occurs particularly when motor run-up times exceed about 5 seconds, e.g. large high speed gas compressors.

   Undervoltage and overvoltage relays are often used on the generators to protect against prolonged overload, seen as undervoltage; and excessive stress on insulation, seen as overvoltage. These relays are usually chosen with adjustable definite time delays.
c) The high starting current of a single large motor may be sufficiently high to be seen by the generators as an overcurrent situation; particularly if a minimum number of the generators are running at the time, and each one is already heavily loaded. This situation may influence the choice of Time Multiplier Setting (TMS) or even the shape of the relay curve. This is illustrated in Figure 12.7.

High voltage generators rated above 2000 kW are usually provided with differential stator current protection (87), which is very sensitive to internal winding faults. Generators have long thermal withstand time constants and can therefore tolerate modest overcurrents for a relatively long time. For these reasons the asymptotic current (current setting) is often set fairly high when compared with other large items such as motors and transformers. Current settings up to 150% are often acceptable, but advice should be taken from the manufacturer of the generator if a high setting is to be used. The TMS of the overcurrent relay will often be set high when the kVA ratings of the downstream transformers and motors are large compared with one of the parallel generators. Overcurrent protection (51 V) of generators tends to be back-up protection to other facilities such as stator differential protection (87). It will be the last protection to operate if all the other facilities fail to respond.

12.2.3 Differential Stator Current Relay

Differential current protection (87) is used for generators to detect internal winding faults, which may develop between phase windings or between a phase and the steel core. Sensitive high-speed action is required in order to minimise the possibility of damage to the stator core laminations in particular. A current as low as 20 amps can cause significant damage if it is allowed to pass to the core

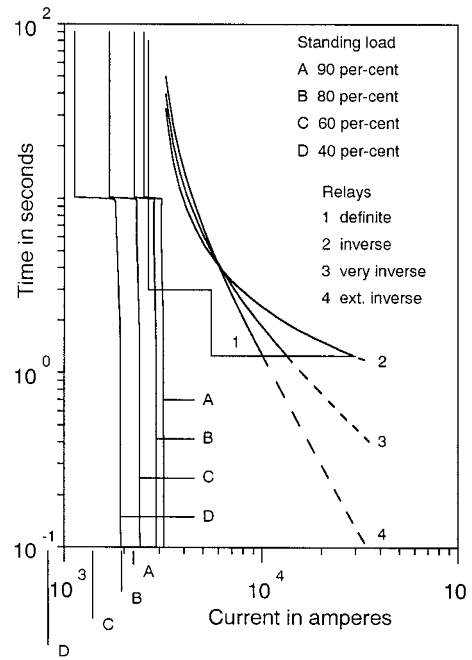

Figure 12.7 Effect of a large load variation on the response of overcurrent relays at the generators. The diagram shows the response when a large induction motor is started direct-on-line. Four different standing loads are shown.

for longer than several seconds, see Reference 2. The relay itself should function in approximately 15 milliseconds, and have a sensitivity of about 2 to 5% of the stator rated current. The nominal setting ranges are between 10 to 40% for 1amp relays and 20 to 80% for 5 amp relays. The low % settings are usually chosen initially and increased if subsequently found to be too sensitive. This type of protection is generally applied to high voltage machines above about 2 MW.

Electromagnetic differential current relays are fitted with restraining or biasing, coils in each secondary circuit of their current transformer. These restraining coils stabilise the relay when large 'through' fault currents are present in the windings i.e. feeding an external fault. Stabilisation is necessary because of mismatch errors and saturation effects in the current transformers, which would otherwise be large enough to activate the sensitive operating coil.

12.2.4 Field Failure Relay

If the field is lost in a generator it will attempt to generate power at a low leading power factor and with a large rotor angle. In most loading situations the generator rotor angle will increase to a critical value where unstable power transfer will occur, and the generator will no longer be able to remain in synchronism with the supply. When synchronism is lost the stator current varies in magnitude over a wide range and at the slip frequency. If this is allowed to continue then it is possible that damage will result in the stator and rotor windings, and the disturbance in voltage at the connected power network will be large enough to cause tripping and overcurrents in loads.

Since the power from the prime-mover cannot be transmitted from the generator there will be a surplus of mechanical power which will accelerate the rotor to a speed greater than the synchronous speed. Since there is also no excitation the only possible conversion of power will be a small contribution due to saliency. The generator will tend to be seen from the power system as a shunt reactor that has a varying X-to-R ratio. Therefore the generator can be shown on an impedance diagram as occupying a region of negative reactance with excursion into both the positive and negative resistance quadrants. If the condition were to be allowed to persist until steady fluctuations became established, then the shape appearing in the impedance diagram would follow a steady locus in the lower two quadrants of the diagram. Consequently a part of this region can be chosen as the response characteristic of a 'loss-of-excitation' relay. A circle is chosen as a suitable shape within the region.

When the field is lost the movement into the critical leading power factor and high rotor current regions takes a finite time, which depends upon the pre-disturbance power being generated and the moment of inertia of the generator and its prime-mover. Consequently the stator current phase angle and power factor can be monitored by a relay located in the stator current circuit, and be set to trip the generator when a critical point is reached.

A field failure relay (40) is usually an 'admittance' relay with an offset admittance zone. The tripping zone is usually determined from a circle. The relay receives a current signal and a voltage signal from the stator terminals. The 'impedance' circle of the generator is determined and located by the following features.

A circle is located in an x-y plane where the x-axis is $-R$ to the left and $+R$ to the right. The y-axis is $+X$ vertically above the x-axis and $-X$ below. The circle is centred in x-y coordinates as $+\Delta R(-(0.5 \text{ to } 0.75)X_d' - (0.5 \text{ to } 1.0))X_d$ where ΔR can be zero or a small positive value. The diameter of the circle is chosen between 0.5 to 1.0 times X_d. All points on the circle must lie in the negative y-axis region. The construction of the circular characteristic of the relay is also described in References 1, 3 and 4.

The reactance settings are converted into admittances by inversion and then used as settings for the relay. The relay setting ranges will usually exceed the requirements of the generator impedance circle. A time delay range of 0.5 to 10 seconds is usually adequate for the protection tripping setting, 3 or 4 seconds would be typical settings.

Example:

Generator details:-

Generator impedance characteristic with zero Excitation.

Rated kVA	S_{gen}	7500
Rated voltage	V_{gen}	6600 V
Rated current	I_{gen}	656 A
Synchronous reactance	X_d	250%
Transient reactance	X_d'	25%
'Sub-transient reactance	X_d''	18%
Voltage transformer ratio		6,600/110 V
Current transformer ratio		800/1 A

Conversion factor for referring the generator reactances to the CT and VT secondary circuits:-

$$X_{sec} = \frac{X_{\text{gen}}\% \times V_{\text{gen}}{}^2 \times CT\text{ratio}}{100 \times S_{\text{gen}} \times VT\text{ratio}}$$

$$= \frac{X_{\text{gen}}\% \times 6600^2 \times 800 \times 110}{100 \times 750{,}0000 \times 1\ 6600}$$

$$= \frac{X_{\text{gen}}\%}{100} \times 5.808 \times 13.333$$

$$X_{sec} = X_{\text{gen}}\% \times 0.7744 \text{ ohms}$$

$$X'_{\text{dsec}} = 25.0 \times 0.7744 = 19.36 \text{ ohms}$$

$$X_{\text{dsec}} = 250.0 \times 0.7744 = 193.6 \text{ ohms}$$

Choose an offset of 0.75 X'_d, a circle diameter of $0.5X_d$. This will allow the generator to run in the leading power factor zone with a large transient rotor angle (up to 120 degrees).

Relay offset = 0.75 × 19.36 = 14.52 ohms

rounded to 15.0 ohms

Relay circle diameter = 0.5 × 193.6 = 96.8 ohms

rounded to 100.0 ohms

Relay time delay, choose 4 seconds.

These results are shown in Figure 12.8.

12.2.5 Reverse Active Power Relay

Reverse active power protection (32) is required to prevent the prime mover from being driven by the generator. This can occur during transient disturbances when a generator is lightly loaded, the

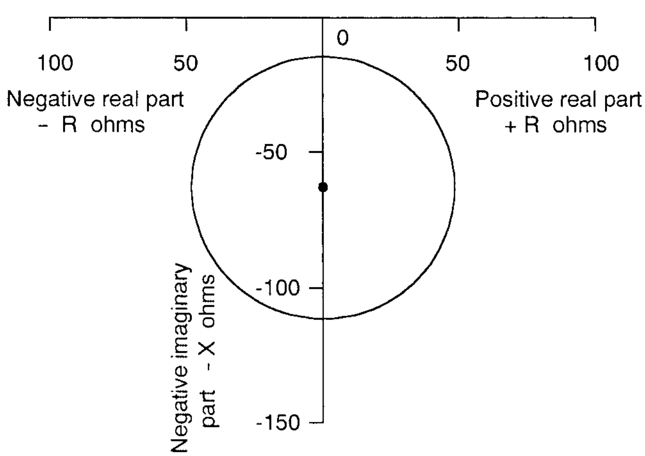

Figure 12.8 Loss of excitation characteristic of an admittance relay. The diagram is drawn in the impedance domain.

power transfer into the generator being from other generators or utility sources in the network. This can occur for example just after synchronising an incoming generator or unloading a generator prior to taking it out of service.

Reverse power protection also protects a gas turbine from failure of its governor control system to regulate its speed e.g. component failure, sluggish response to speed changes. When power is fed back to the prime mover it will tend to cause the shaft speed to rise, and the governor control system will attempt to reduce the fuel supply by closing the fuel valve to its lower limit. In these circumstances the prime mover is effectively without speed control.

Gas-turbine generators up to above 35 MW are usually driven by the prime mover with a speed-reducing gearbox, because the generators are usually 4-pole low-speed machines. The design of the gearbox and the couplings may not permit prolonged reverse power operation.

The relay is usually set for 1 to 5% of rated power and with a tripping time of up to 5 seconds.

12.2.6 Negative Phase Sequence Relay

A negative phase sequence relay (46) protects a generator against overheating of its rotor pole faces and damper bars. This form of overheating is due to the presence of unbalanced stator currents, which create a negative phase sequence (NPS) flux in the air gap. This flux rotates in the opposite direction to the rotor but at the same absolute speed. Hence the rotor poles and damper bars have double-frequency currents induced into them, which rapidly cause localised heating and eventually distortion of the rotor and slot damage. The NPS current has a heating characteristic similar to the familiar positive phase sequence overcurrents and fault currents, i.e.:-

$$K_n = I^2{}_2 t$$

Where K_n is typically 50 to 60 for air-cooled generators.

Salient pole generators used with gas-turbine drivers can tolerate NPS currents up to 40% of full-load current, when defined by:-

$$I^2{}_2 t \leq 0.4 I^2{}_1 t, \quad \text{for large values of time } t.$$

The relay characteristic therefore has a negative slope of 2 on a log-log scale, and the value of K_n is determined by biasing the sloping line up or down on the log-log scale. A setting for K_n in the relay is chosen between 5% and 30% depending upon the actual K_n value of the generator. A typical relay has an operating time of 10 seconds when 100% NPS current flows in its circuit, and the time multiplier setting (TMS) is set at 100% or 1.0 pu. The relay should be insensitive to zero sequence and third harmonic currents (otherwise externally connected star/delta interposing current transformers can be used to achieve this requirement).

12.2.7 Stator Earth Fault Relays

12.2.7.1 Standby earth fault relay

High voltage generators used in the oil industry are usually earthed by connecting an impedance, which is invariably a resistor, between its star point and the ‘ground’. Occasionally generators are unearthed; but in such cases earthing of the power system is provided artificially at the busbars to which the generators are connected.

The star-point connection to earth is provided with a current transformer and a sensitive relay. The relay (5I G) is of a definite time delay or inverse time delay type so that it can be graded as back-up protection to earth fault relays at downstream feeders and consumers.

The choice of the current setting depends upon several factors:-

- High or low impedance earthing.
- Level of continuous third harmonic current that will flow in the impedance.
- Capacitance of downstream feeders, i.e. AC charging current.
- Earth fault relay settings of downstream relays.
- Differential current relay (87) settings of the generator.

Up until about 1985 it was common practice to limit the fault current in the stator windings and neutral earthing resistor to between 50% and 100% of the full-load current. However, there has been a move away from choosing such high levels of current and it is not uncommon to choose values in the range 20 to 50 amps, and occasionally as low as 10 amps. This later approach is due to research by machine manufacturers which has shown that serious burning damage to the iron core begins to occur at about 20 amps, see References 2, 5, 6 and 7.

The thermal withstand time for the neutral earthing resistors are usually specified as 10 seconds for the duration of the fault current. This allows adequate time for main and back-up protection relays to operate and clear the fault. The standby earth fault relay (5I G) time-current characteristic must be chosen so that its I^2t curve is lower than that for the neutral earth resistor and the connecting cables. (The I^2t curve is derived directly from the I-t data, and not by integrating the curve.)

In some generating schemes e.g. drilling rigs, emergency supplies, where the nominal system voltage is less than 1000 volts, it is possible to operate them as 'unearthed' systems. This occasionally applies to low-voltage systems, which do not use the neutral as a 4-wire method of supplying unbalanced loads (unbalanced loads are taken between the lines, often by using a step-down transformer). However, the normal practice in these schemes is to use an earth leakage detection relay which has sensitivity between a few milliamps and 0.5 amp. The relay normally gives an alarm so that the operator of the system is aware that a fault is present somewhere in the system, and this can then be located at a convenient time. If a second earth fault occurs on a different phase then the overcurrent relays will see the fault as a phase-to-phase short circuit and will trip an appropriate circuit breaker, or a fuse in the system will operate.

12.2.7.2 Restricted earth fault relay

In order to restrict the detection of earth faults to those within the stator winding, and those from the stator terminals to the switchgear current transformers, a sensitive relay (64) is used. Three current transformers are used in the stator live lines and one in the star to NER connection. All four current transformers are connected in parallel such that any unbalance in the currents due to an 'internal' fault is detected by the restricted earth fault relay (64). A sensitive high impedance relay is used to achieve an instantaneous response. However, if a high impedance is connected across a current transformer it is possible that very high voltages will appear across the impedance. This is due to the action of the current transformer to balance the ampere-turns across its windings. It is the normal practice to shunt the relay with a non-linear resistor. As the voltage across the resistor and the relay rises above a predetermined value, the resistor shunts more and more current from the current transformer. In so doing the relay voltage is moderated, and the relay functions as required.

The choice of current or voltage setting for the relay will depend upon the design value of earth fault current that will pass in the NER during the specified time e.g. 20 amps for 10 seconds. If the setting is too low the relay may respond to stray and harmonic currents in the neutral circuit. The maximum expected third plus triplen currents should be determined and the relay set at say double their combined level, or higher.

It is worth noting that the stator differential relays (87) will not normally be sensitive enough to detect the low earth fault currents that are limited by a high resistance NER. With the modern practice being to limit these currents to typically 20 amps, it is necessary to install the restricted earth fault relays (64).

12.2.8 Over Terminal Voltage

If the terminal voltage of a generator persists above about 110% of its nominal value then it is possible that the automatic voltage regulator (AVR) of the generator has developed a fault within its control circuits. (An alternative cause, in the case of generators having a high neutral earth resistance, is that an earth fault on one phase is present.)

Excessive terminal voltage from the generator implies that the exciter is being forced to produce a high rotor current in the generator. Consequently both the generator itself and its exciter are being overstressed in terms of current, and therefore may become overheated.

Since the generator is supplying the power system at an elevated voltage, all the transformers and consumers near to the generator will receive an excessive voltage. In this situation transformers and motors in particular may well be overexcited and their magnetising current will rise sharply. Excessive magnetising current may be accompanied by overheating of the iron core laminations. Other consumers such as inverters, battery chargers, light fittings, electronic systems may also react unfavourably to excessive supply voltage.

If several generators are operating in parallel and one of them has a faulty AVR then the healthy generators may become underexcited as their AVRs respond to the high system voltage. This situation could lead to unstable operation if the generator rotor angles become too large.

To protect the system from prolonged high voltage it is the usual practice to install an over-voltage relay (59) in each of the generator circuit breakers or at their common busbar. The relay settings are usually set to operate at 115%, with a time delay between 0.5 and 10.0 seconds.

12.2.9 Under Terminal Voltage

Prolonged undervoltage implies that there is a fault in the AVR or that there is an excess current being drawn from the generator. An excessive current could be due to a fault in the system or an overload caused by, for example, a loss of a generator without a corresponding shedding of load. If the cause is excessive current but the voltage is still high enough to maintain the consumers, then the overcurrent protection of the generator may take too long to operate, particularly if a voltage-restrained relay is used. An undervoltage relay (27) is used to trip the generator if the voltage falls below a fixed level for a definite time. Typical settings are 90% of the nominal voltage and between 0.1 and 10.0 seconds. A longer delay may be needed if large motors with long run-up times are started directly on line at the same busbars that are fed by the generators. This relay will need to coordinate with a similar relay used at the busbars to shed consumers when an overloading situation is apparent from a prolonged low busbar voltage.

12.2.10 Under- and Overfrequency

Generators normally operate over a narrow frequency range, as determined by their prime-mover speed regulating controllers, typically 1 to 2 Hz for high loadings. Speed regulation is basically proportional control action, with a 'droop' gain giving a 4% droop of speed over the range of zero to full load. Simple situations have a fixed no-load frequency of 102 to 104% and allow the frequency to fall to 98 to 100% at full-load. Occasionally a power system is operated with its steady state frequency fixed at 100%, by the use of integral control action. This is called 'isochronous governing', and it requires special control circuits for each generator in the power system if several generators need to operate in parallel.

Under- and overfrequency relay (81) operation implies that the system frequency is outside a range of, for example, 96 to 106%. In both cases this generally will indicate that the speed-governing controllers are not functioning correctly. Underfrequency will usually be accompanied by a heavy active power demand, which will also cause the stator current to be high. If the load power factor is similar to the rated power factor of the generators (usually 0.8 lagging) then the overcurrent protection will probably function before the underfrequency protection. Most power systems have a high load power factor above 0.9 lagging, which provides some margin of operating time between overcurrent and underfrequency protection.

Underfrequency protection can operate in several stages in a progressive manner to enable the generators to recover their frequency. Several stages over a range of say 100% down to 96% would be used, initially to shed the connected loads and finally to trip the generators. Time delays of several seconds would be used at each stage, to allow the speed regulators to respond and the loads to settle to a steady state. This subject is discussed in more detail in Appendix D.

12.3 EMERGENCY DIESEL GENERATORS

Emergency diesel generators occasionally operate at high voltage e.g. 3300, 4160, 6600 volts. They are used in plants that consume high levels of power and which are sensitive to the loss of supply. Liquified natural gas (LNG) plants are typical examples where high voltage emergency generators are installed. The refrigeration processes and storage tank facilities need to be maintained in an operating state until they can be carefully shutdown.

Low voltage is most commonly used for emergency power services. Emergency generators need to operate in difficult situations and may be called upon to continue until fuel is exhausted or until physical destruction takes place. The second scenario is occasionally adopted for offshore facilities, where safety of personnel is paramount. Personnel need to be evacuated under all weather conditions and when there is a dangerous situation onboard the facility. Hence lighting, public address, navigational aids, radio etc. need to be kept operating for as long as possible.

In view of the need to continue operation it is possible to tolerate some relaxation in the protective relays that are provided for emergency generators, especially low voltage offshore machines. The following relays in sub-section 12.2.1 may therefore be deleted for low voltage generators:-

- Negative phase sequence (46).
- Differential stator current (87).
- Field winding earth fault (58).

In addition the current setting of the overcurrent relay (51) may need to be higher than for a 'normal service' generator. The voltage-restraining element of a 51 V relay may not prove to be particularly beneficial for low voltage emergency generators.

12.4 FEEDER TRANSFORMER PROTECTION

Power systems for offshore platforms and onshore plants, which have their own generators seldom have feeder transformers with ratings greater than about 10 MVA. These transformers usually feed radially to the consumer switchboards. Several levels of operating voltages are used in these situations, for example:

a) Generators and main distribution HV switchboards.

Voltages: 13,800, 11,000, 10,000, 6600, 6000 volts,

occasionally 4160 and 3000 volts.

b) Secondary distribution HV and LV switchboards.

Voltages: 6600, 6000, 4160, 3000, 600, 440, 400, 380 volts.

c) Sub-circuits

Voltages: 254, 240, 230, 220, 120, 110 volts.

The power system frequency is either 50 or 60 Hz.

The construction of transformers will be either liquid insulated in a steel tank or cast resin in a safety enclosure. Either type can be used for outdoor and indoor services, although additional weatherproofing will be needed for cast resin units.

For transformers having ratings up to 10 MVA the following protection schemes would normally be provided:

Typically schemes for different transformer configurations that contain most of the following relays are shown in Figures 12.9, 12.10 and 12.11.

- Overcurrent.
- High-set or instantaneous current.
- Primary earth fault current.
- Secondary earth fault current.
- Differential current.
- Winding and core high temperature.
- Buchholz oil tank surge protection.

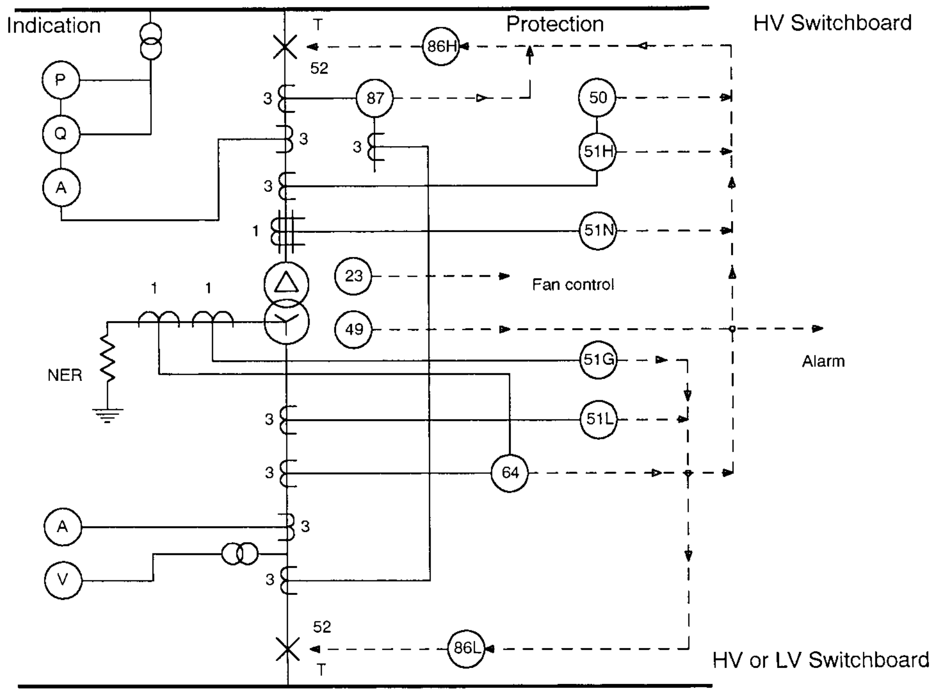

Figure 12.9 Protection devices for a two-winding transformer with NER.

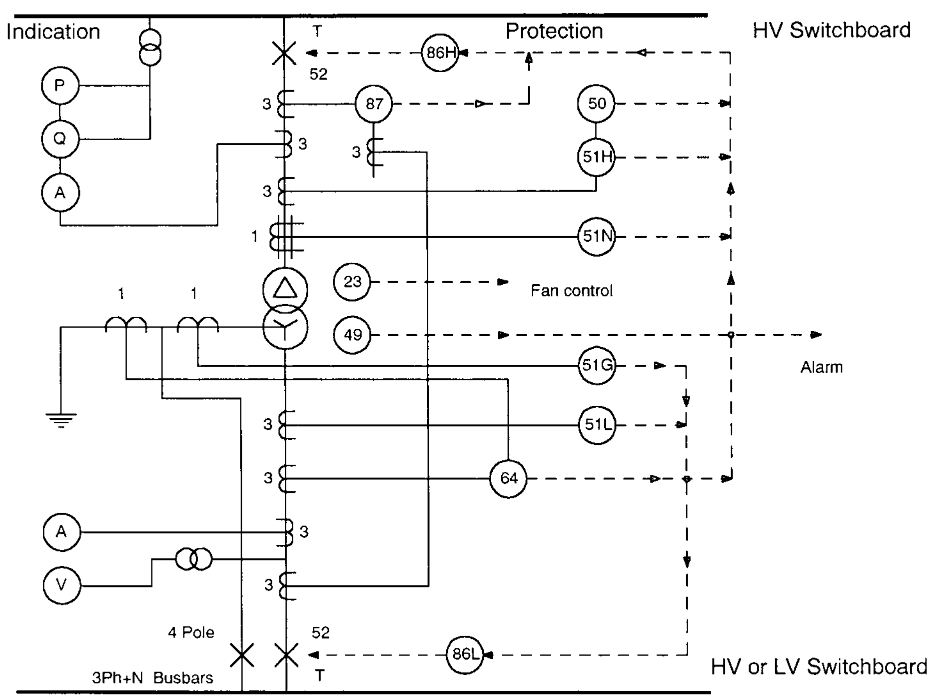

Figure 12.10 Protection devices for a two-winding transformer with solid neutral.

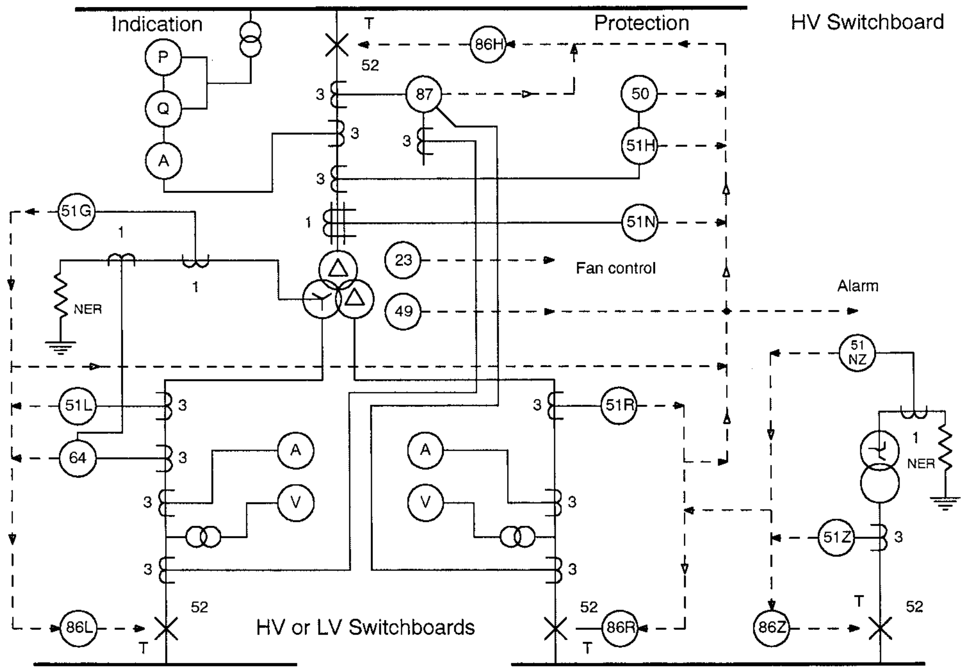

Figure 12.11 Protection devices for a three-winding transformer.

The number of these protection schemes applied to a particular transformer depends upon several factors e.g.:-

- Critical nature of the load e.g. emergency, essential, normal production.
- Single or duplicated feeder.
- Nominal kVA rating of the transformer.
- Secondary winding voltage.
- Primary winding switching device.
- Physical location and availability of spare complete units or parts.

Figure 12.9 applies to a delta-star transformer that feeds a high or low voltage switchboard. In this case the secondary winding star point is earthed through an impedance, shown as a resistance. The NER could also be an earthing inductor or a transformer with a secondary winding feeding a resistance load, as explained in sub-section 13.3.1. The use of earthing transformers in the oil industry is seldom encountered, it is more commonly found in EHV systems operated by power utility companies.

Figure 12.10 is almost the same as Figure 12.9, the difference being that the star point of the secondary winding is solidly earthed, which is usually the case with low voltage secondary systems.

Figure 12.11 is again similar to Figure 12.9 but applies to a three-winding transformer. Three-winding transformers are occasionally used in the oil industry. The most common application is with drilling rigs that are located at offshore production platforms, where they share the power generated by the production facility. Drilling rig DC systems are fed from a 600 V unearthed system, which makes the use of a delta winding attractive. This delta winding acts like a tertiary winding in that it helps to suppress harmonics from being transferred to the primary winding and HV system.

Transformers used for offshore services will generally have more protection schemes applied, than those for onshore services. This is due to the cost of lost production caused by failure of main power supplies, and the difficulties that arise when a failed unit needs to be replaced. Cast resin transformers are often preferred for offshore services because of their higher reliability, simpler and safer construction and ease of maintenance.

12.4.1 Overcurrent

An overcurrent situation is more likely to be caused by excessive secondary load or a serious fault at the downstream switchboard than an internal fault. Overcurrent protection can be regarded as currents that are above 100% but below about 500% rated current. Currents above about 500% rated current can be regarded as 'high-set' or 'instantaneous' currents, and these are protected in a different manner than for overcurrents. It is feasible, therefore, to treat the overcurrents as a 'through-fault' condition and detect them in either the primary or the secondary winding switchgear, but not necessarily at both windings. Detecting overcurrents at both windings would appear to be a desirable requirement, but it can introduce the need to coordinate the protection curves of the two relays. These could often be different types of relays or even be made by different manufacturers, in which case their curves may not match satisfactorily. Alternatively the relays, or their curves, could be chosen to be the same, or nearly the same. In this case their settings could be made the same and whichever relay operates first can be used to trip the circuit breakers in both windings, either directly or through intertripping circuits.

The characteristic curve of the overcurrent relay(s) can be chosen from several standard shapes:-

- Definite time.
- Standard inverse time.
- Very inverse time
- Extremely inverse time.

Definite time relays are chosen when the individual secondary loads are small when compared with the transformer rating, and when motor run-up times are small i.e. up to 1 second. Care must be taken to match the current–time settings to the thermal characteristic (I^2T) of the transformer. (A good guide to estimating the I^2t characteristic for a liquid insulated transformer, when data from the manufacturer are not available, is the ANSI/IEEE standard C57.12–1980 which takes into account the probability of frequent through faults and the ratings of the transformers. Note, in this connection plants which do not use or are not fed from overhead power lines would be regarded as having infrequent through faults.) Definite time relays are the least expensive of the four types and easy to set up. They are seldom used for offshore platform applications.

When an individual load is a large induction motor which is started direct-on-line and has a long run-up time, then the standard or very inverse time relays are often chosen.

Very and extremely inverse relays are used in systems where the fault level downstream is low when compared with that available at the point of main supply, e.g. a main generator switchboard. They are also used where coordination with upstream or downstream fuses is necessary.

Extremely inverse relays have an inverse square law characteristic, which predominates at high fault currents. It therefore closely matches the I^2t characteristics of cables, motors, transformers, NERs etc.

12.4.1.1 Comparison of inverse time curves

Before electronic relays were developed the standard inverse characteristic was taken as the reference e.g. in BS142 for UK practice. A point on the characteristic was chosen for the comparison with others, e.g. extremely inverse. The reference point was 10 times the nominal relay current and an operating time of 3 seconds.

Most literature for modern relays, and the IEC60255, do not compare the characteristics in this manner. Instead they use a standardised formula for each relay,

Inverse time

$$t = \frac{0.14}{\left(\dfrac{I}{I_n}\right)^{0.02} - 1} \quad \text{seconds}$$

Very inverse

$$t = \frac{13.5}{\left(\dfrac{I}{I_n}\right)^{1.0} - 1} \quad \text{seconds}$$

Extremely inverse

$$t = \frac{80}{\left(\dfrac{I}{I_n}\right)^{2} - 1} \quad \text{seconds}$$

Where the numerator is a constant that falls within the range of the time multiplier of the relay. If the numerator is 'temporarily' modified then the characteristics can be compared in a similar manner to the older method of BS142. A good pictorial comparison can be made by choosing the common point to be at 5 times nominal current and 5 seconds operating time. The modified numerators are 0.1636, 20.0 and 120.0 respectively. The three characteristics are shown in Figure 12.12. It is feasible with modern electronic relays to use any value for the exponent in the denominator. Figure 12.13 shows a family of curves in which intermediate values of the exponent are included, i.e. 0.5, 1.5 and 3.0.

12.4.2 High-Set or Instantaneous Current

12.4.2.1 Basic considerations

The use of high-set or instantaneous current protection for the primary winding, or the secondary winding, is determined by several factors, which differ for either winding. Consider the primary

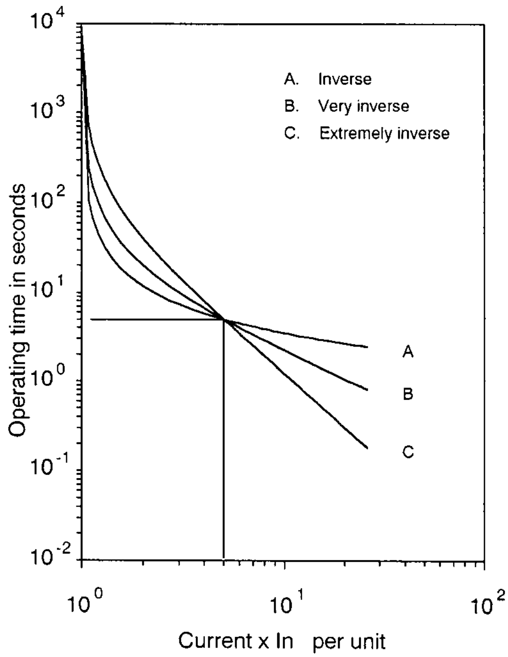

Figure 12.12 Various standard inverse time characteristics of a time-dependent overcurrent relay.

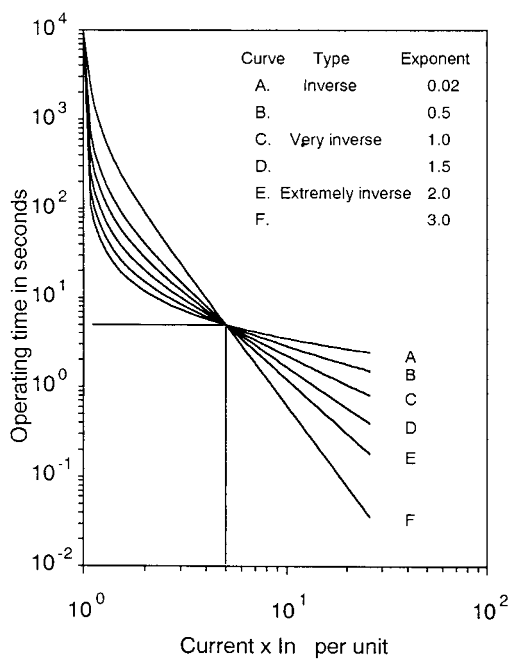

Figure 12.13 Various non-standard inverse time characteristics of a relay.

winding. Instantaneous protection is applied to respond to major three-phase faults at or near to the primary terminals e.g. in the main terminal box or chamber. It should not be used to detect major faults in the secondary winding or its downstream circuit. The settings for the primary instantaneous protection can therefore be chosen to be relatively high. However, the choice may be influenced by the upstream source of fault current e.g. the number of generators, another transformer, a utility connection, as explained in sub-section 12.5.2.2.

The situation for the secondary circuit is different. The purpose of instantaneous protection is to detect major faults at or near to the secondary terminals and at the downstream switchgear e.g. busbar fault. This protection must also be coordinated with the instantaneous protection settings of downstream circuits e.g. static loads, motors. The settings chosen are much less sensitive to the upstream source characteristics than those of the primary protection, because of the inclusion of the leakage impedance of the transformer in the faulted circuit.

12.4.3 Characteristics of the Upstream Source

Where the upstream source is another transformer, or a utility connection, the calculation of the three-phase fault current is straightforward and it will not usually vary significantly with the operating configuration of the upstream network.

If the upstream source is one or more generators then the situation is more complicated, especially for the transformer primary protection. When a major fault is applied near to generators they respond in a complicated manner due to the sub-transient and transient dynamics of their windings and to the dynamic response of their voltage regulators. The response from their windings is also modified by the impedance connected between the generator terminals and the point where the fault is applied. The sub-transient and transient direct-axis time constants, governing the decay of fault current, change with the amount of impedance added to the fault circuit. As this impedance increases from zero to a large value, the time constants change from their short-circuit values to their open-circuit values, see 7.2.11 and 20.3.2. The inclusion of the impedance reduces the fault current, which is more significant when only one generator is operating. The decrement of fault current can be plotted on the coordination graphs for the various operating situations. In the example of sub-section 11.9 and 12.1 there are four or more generators and therefore the two main situations to consider are four generators running and only one generator running.

12.5 FEEDER CABLE PROTECTION

The type of feeder cables described in this section are those between switchboards within an oil industry site, rather than those between a utility power plant and an oil industry site. These feeders may be described as primary feeders as opposed to secondary feeders downstream in the system. Feeders from a utility power plant or a transmission network have protective relaying systems that are more sophisticated than those described herein, e.g. multi-zone distance protection, admittance relays, carrier protection schemes.

Two basic requirements apply to feeder cables, firstly to protect the cable from overcurrents, which may be related to the connected load, and secondly to detect faults along the length of the cable.

12.5.1 Overcurrent Protection

Overcurrent protection is usually provided by a (51) relay, which has separate elements for each phase. The overcurrent curve should be chosen with a margin below the I^2t characteristic of the cable, and to coordinate with the protective devices downstream e.g. an exceptionally large consumer at the switchboard being fed by the cable. The type of curve may be inverse, very inverse or extremely inverse, depending upon the coordination required downstream and the margin between the current rating of the cable and its expected loading.

For cables having long route lengths the associated volt-drop may cause the margin in current capacity to be reasonably high, especially with low voltage feeders.

12.5.2 Short-Circuit Protection

Short circuits that do not involve earth, and which are within the length of the cable, can be detected by setting the instantaneous elements of the overcurrent relays to a value of current calculated at the receiving end of the cable that flows into a zero-impedance fault. Customarily this fault is a three-phase fault for which the calculations are straightforward. If the fault is beyond the cable for example in a consumer then the fault current will be less and should be cleared by the consumer protective device. The feeder cable relays will then act as a back up to the consumer relays.

If the feeder cable is protected by fuses then these should be chosen to rapidly clear an internal line-to-line or three-phase fault. They should be supplemented with a (51) relay to provide overcurrent protection.

High voltage cables that provide a critical service, that are to be operated in parallel or will have a long route length in an area of high risk of damage, should be protected by a high speed differential current scheme. The most commonly used is the Merz–Price scheme. Each sending end and receiving end line of each cable is equipped with a matched current transformer. At the sending end switchgear is placed the (87) relay to detect an out-of-balance current due to a fault within the cable. The operating time for this scheme is typically 5 or 6 cycles of fundamental frequency current.

An alternative and less expensive scheme uses a core-balance current transformer at the sending end of each cable. Such a scheme is shown in Figure 12.14.

12.5.3 Earth Fault Protection

When a cable is damaged accidentally from external means, such as digging in a trench, it will nearly always cause an earth fault. The earth fault current may flow in the surrounding earth or in the armouring metal; or a combination of both routes. The magnitude of the earth fault current will depend to a large extent on how the sending end star-point upstream of the cable is earthed. For most high voltage systems the star-point is earthed through an NER that limits the current to between 10 and 100 amps. Most low voltage systems are solidly earthed at the star-point of the supply. There are the occasional exceptions to these methods. The usual method of detecting an earth fault in a cable feeder is to use a core balance current transformer in conjunction with a sensitive 50 N relay.

A time delayed 51 N relay may be preferred so that some coordination and back up can be provided to downstream devices. The primary feeder should not trip in response to a fault in a consumer circuit. The consumer circuit should have its own fast-acting earth fault 50 N relay or element.

Often the earth fault 50 N or 51 N relay is an integral part of the overcurrent relay. These integral relays usually have various options which can be simply switched into the scheme as required.

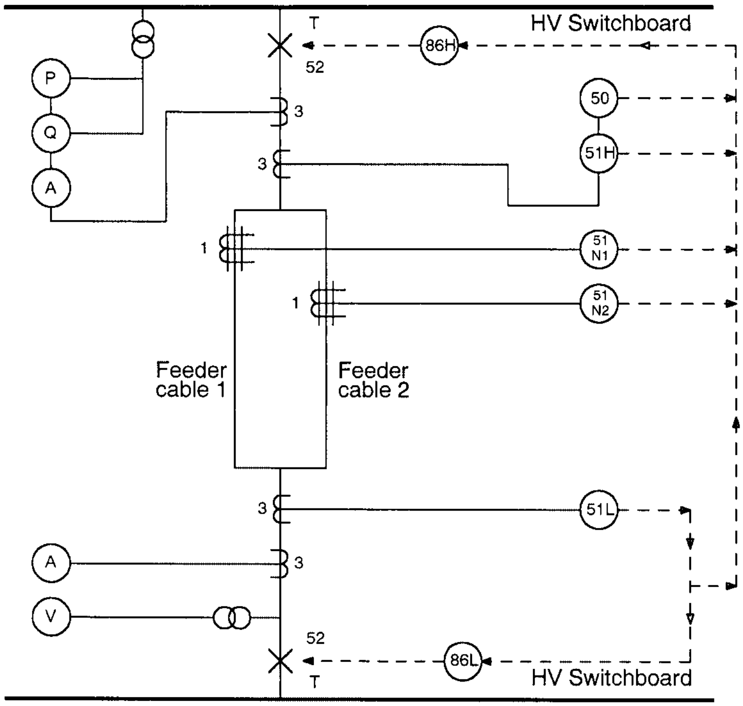

Figure 12.14 Protection devices for a high voltage feeder cables.

12.6 BUSBAR PROTECTION IN SWITCHBOARDS

Faults can occur within the busbar and riser compartments of switchboards. However, modern switchgear is very reliable and such faults are rare. Many purchasers of switchgear specify insulated and segregated busbars and risers, with all the connectors, clamps, nuts and bolts to be fully shrouded with flame retardant material, see sub-section 7.2.4.

12.6.1 Busbar Zone Protection

For switchboards to be operated at voltages up to approximately 15 kV it is common practice to avoid using differential busbar zone protection. If it is necessary to provide the maximum practical availability of supply then busbar zone protection should be considered.

If the fault level at the high voltage busbars is high and close to the rating of the switchgear then busbar zone protection should be given serious consideration. Busbar zone protection is usually based on the Merz–Price circulating current scheme, with high impedance (87) relays.

Where a bus-section circuit breaker is used to divide the busbars (during abnormal operating conditions) each set of busbars is protected as a separate zone. Each zone consists of the incomers, the outgoing circuits and the bus-section circuit breaker(s). An accurate current transformer is connected in each line of each circuit. All the current leaving the zone must be balanced by current from the incomer circuits. A fault in the zone will be detected by the (87) relay. Rapid operation is required to open the incomer and bus-section circuit breakers so that the fault does not develop and spread as a fire or blast along the busbars.

12.6.2 Overcurrent Protection

It is not normally necessary to provide overcurrent protection in the bus-section circuit because the presence of overcurrent, not caused by an in-zone fault, would be detected by an outgoing circuit relay. For the busbar to be overloaded the outgoing system must also be overloaded. Introducing an overcurrent relay in the bus-section circuit will add complication to the coordination of the incoming and outgoing relays, since a time margin is necessary between each relay. In systems where there are large induction motors the coordination can already be awkward to achieve.

12.6.3 Undervoltage Protection

If the busbars are being operated at an unusually low voltage then the consumers may attempt to consume their full power. If this happens they will take in more than their rated current, which is a potentially damaging condition. If the switchboard supplies one or more large induction motors then during their starting process they will draw a heavy current. Should the motor experience difficulty during starting then a prolonged period of high current will occur and this could cause a depression in the busbar voltage. Such a depression may adversely affect other consumers.

Undervoltage operation is undesirable and therefore a suitable relay (27) with a time delay is often used, especially in high voltage switchboards. A similar problem can arise with main generator switchboards. If a generator is suddenly tripped then the remaining generators must try and supply the load. Each of these generators will experience a sudden increase in current and a drop in terminal voltage. The load will react to the drop in voltage. The automatic voltage regulators will try and restore the voltage. If the load is predominately induction motors then they will all try and accelerate back to their normal speed. The acceleration will be accompanied by an increase in their reactive current which will aggravate the volt-drop and delay the voltage recovery. If the depression is more than at least 20% and lasts for more than 0.2 to 0.5 seconds then there is a risk that the system of induction motors will fail to recover, see also sub-section 7.6.1.

The (27) relays should have an adjustable voltage range to cover for the 80% voltage condition, typically 50% to 100%. The relay should have a time delay that is adjustable up to at least 0.5 second.

The relay may be set to trip all the outgoing circuits on its section of busbars. Alternatively a more selective method can be used in which the largest consumers are tripped initially. If the initial tripping fails to produce a good recovery then a second level of tripping may be used for the remaining consumers.

During the studies that are usually carried out for system stability, starting large motors, loosing a generator etc., a study of undervoltage (and overvoltage) should be included. Several scenarios should be considered so that a good compromise between voltage depression and its duration can be found for setting the (27) relays.

Undervoltage schemes are often included in the reacceleration control systems of individual motors or groups of motors. However, these are more appropriately considered in motor protection rather than busbar protection schemes.

12.7 HIGH VOLTAGE INDUCTION MOTOR PROTECTION

Most oil industry plants use high voltage induction motors to drive pumps and compressors. Unlike industries that take power from a utility the oil industry usually generates its own power. Most utility companies restrict the size of induction motors that are to be started direct-on-line. This restriction seldom applies in the oil industry. There are some applications where direct-on-line starting is avoided e.g. large compressors in LNG plants, but these may be regarded as special cases. The starting time for high voltage induction motors varies typically from one second to as long as 30 seconds. Pumps and low speed machines tend to have the shorter times. A high-speed compressor driven through a gearbox will usually have a long starting time.

High starting currents and long starting times can give rise to difficulties in choosing suitable protective relays for the motor. Not all motor relays have a wide enough range of settings to adequately protect the motor during the starting time.

High voltage induction motors are normally provided with the following protective devices, some or all of which may be incorporated in the one device (occasionally called a motor managing relay). Modern motor relays are based on microcomputer technology and these relays not only provide most of the protection functions but also provide a full range of measurements, indications and alarms. They also communicate by media such as fibre optics through networks to management and SCADA computers, see also sub-section 7.6.2.

a) Main functions:
   - Overloading or thermal image (49).
   - Instantaneous or high-set overcurrent (50).
   - Negative phase sequence (46).
   - Core balance earth fault (51N).
   - Differential stator current (87).

b) Additional functions:
   - Stalling current.
   - Limitation to the number of successive starts.
   - Undercurrent (37).
   - High winding temperature.
   - High bearing temperature.
   - Excessive vibration.

Figure 12.15 shows the application of the above functions to small and large high voltage motors.

Most modern electronic motor relays are designed to meet the requirements of IEC60255 Part 8. This standard defines the thermal image or overloading curves of the relay. Some modern motor relays are very sophisticated and their literature needs to be studied carefully in order to ensure that the relay chosen fully satisfies the characteristics of the motor. Not all manufacturers use the same terminology to describe the functions of their relays. This makes the process of comparing different makes and models of relays somewhat difficult.

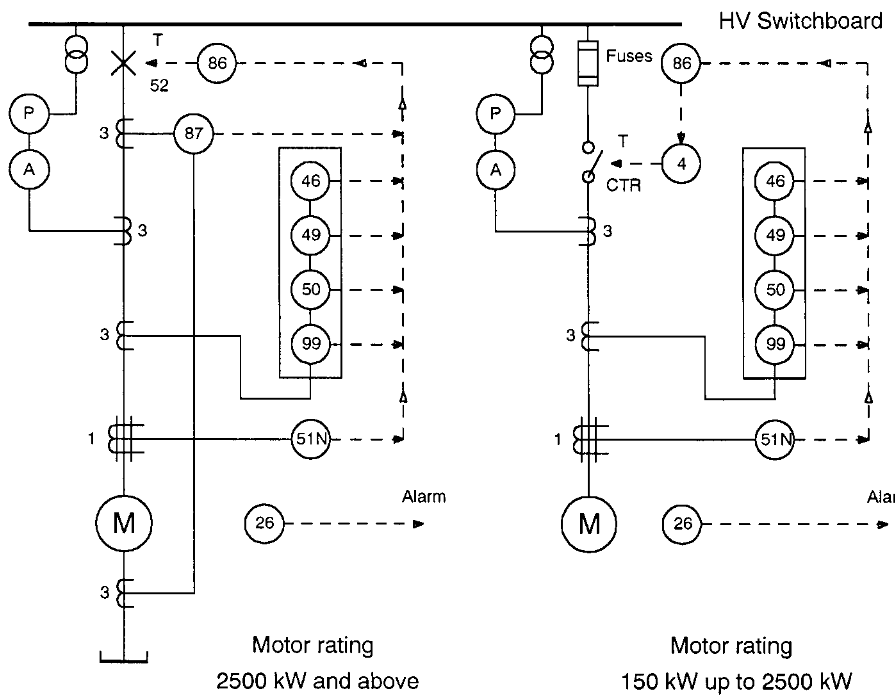

Figure 12.15 Protection devices for high voltage motors.

12.7.1 Overloading or Thermal Image

As with most electrical power equipment the thermal characteristic is based on an I^2t law. The equation for the thermal image as given by IEC60255 Part 8 when the motor is cold is,

$$t_c = T_{\text{th}} \log_e \left[\frac{I^2}{I^2 - {I_o}^2} \right] \text{ seconds}$$

Where I = Relay current as a multiple of the nominal current, pu.
I_o = Reference current in pu that determines the position of the asymptote, e.g.
at $t_c \to 10{,}000$ seconds. I_o has a typical value between 1.015 and 1.065.
T_{th} = Thermal time constant in seconds, usually given in minutes for a particular motor.

Note: The equation is only valid for $I > I_o$.

A similar equation is used for the hot condition of the motor,

$$t_h = T_{\text{th}} \log_e \left[\frac{I^2 - {I_p}^2}{I^2 - {I_o}^2} \right] \text{ seconds}$$

Where I_p = motor load current before the overload, pu.

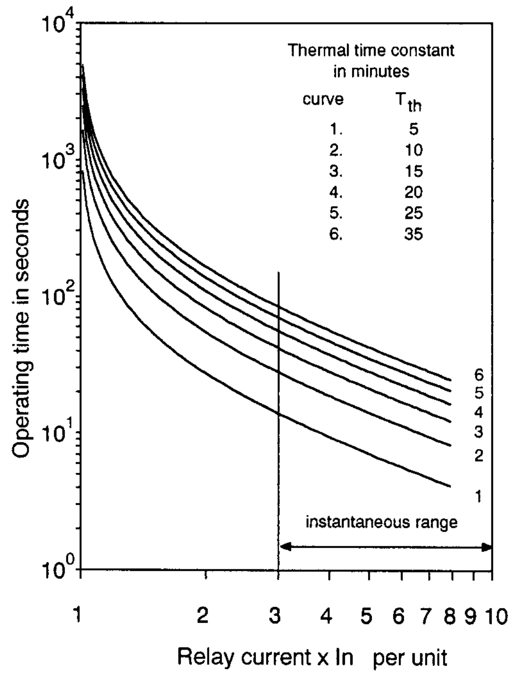

Figure 12.16 Operating time of a motor thermal image relay. The motor is assumed to be running fully loaded before the fault occurs.

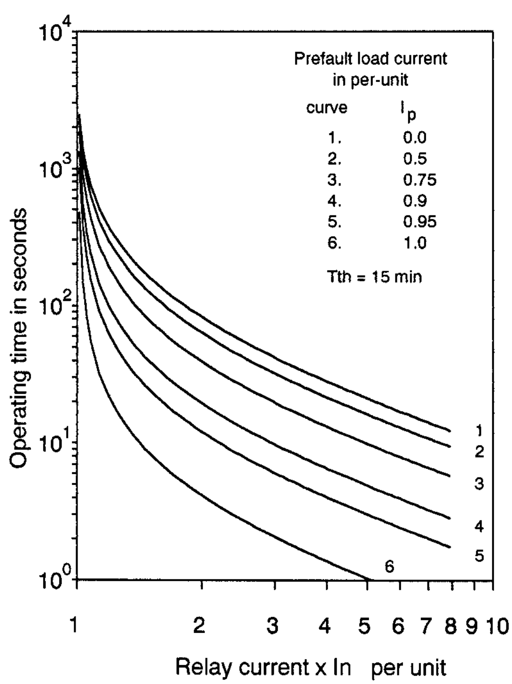

Figure 12.17 Operating time of a motor thermal image relay. The effect of the motor being partly loaded is shown.

When the t_c and the t_h functions are plotted with log-log scales they exhibit slight curvature at the higher multiples of nominal current. Figures 12.16 and 12.17 show the thermal image and the effect of pre-fault load current. Some manufacturers incorporate a feature where this curvature is removed at the high currents, and follows at the conventional I^2t straight line when plotted on log-log scales. For a given relay current the hot time t_h for a fully preloaded motor will be approximately one-sixth to one-tenth the value of t_c. Some relays allow this ratio to be preset over a wider range.

12.7.2 Instantaneous or High-Set Overcurrent

In order to protect against prolonged winding or terminal box faults it is the usual practice to include an instantaneous tripping function. The range of the setting is typically 3 to 10 times the relay nominal current.

High voltage motors are often controlled by a contactor (CTR in Figure 12.15) that has a high-speed fuse just upstream and mounted in the same compartment of the switchboard. The contactor must have sufficient I^2t capacity to handle the let-through fault current until the fuse completes its function. It is necessary under this situation to delay the opening of the contactor. Consequently the relay should either have an adjustable delay for contactor services, or it can send its tripping signal to a separate self-resetting timer (2). Upon timing out the timer trips the contactor (4). The minimum delay setting is typically 0.2 seconds. Advice should be taken from the switchgear manufacturer for the actual delay to use for a particular motor circuit. (Small kW rated low voltage motors are also controlled by contactors and the same precaution is necessary.) The contactor may be overstressed during the passage of fault current, and in order to minimise the stressing the requirements of IEC60632 Part1 Appendix B, Type C, should be adopted when specifying the switchgear, see sub-section 7.3.2.

12.7.3 Negative Phase Sequence

As with the rotors of generators the presence of negative phase sequence currents in the rotor of an induction motor causes detrimental heating. The cause of the negative phase sequence currents could be an internal or an external malfunction. An internal malfunction may be a minor or major phase-to-phase fault in the stator windings. An external malfunction could be a depression in one of the incoming phase-to-neutral or phase-to-phase voltages. The motor will then be fed from an unbalanced source of voltage, and will respond by creating unbalanced currents in its stator and rotor conductors.

Modern relays include a function for detecting the negative phase sequence currents, with settings typically in the range of 10% to 50% of the nominal relay positive sequence current. High power rating motors may need a lower limit than 10%.

Since rotor heating can be caused by excessive positive sequence current as well as the presence of negative sequence current it has become the practice in some relay designs to combine these heating causes.

The shape of the curve for negative phase sequence current operations varies with the manufacturer. Some prefer an $I_2{}^2t$ whilst others an inverse time characteristic. Time settings are typically in the range of 10 to 120 seconds.

12.7.4 Core Balance Earth Fault

Earth faults that occur within the stator windings will usually involve the iron laminations. Such faults can cause a considerable burning type of damage to the iron and windings if not either limited in magnitude by the supply NER or by tripping the motor rapidly. The discussion given in sub-section 12.2.3 for generators applies in the same manner for high voltage motors.

It is therefore necessary to provide a sensitive method for detecting earth fault currents. The most common method is to provide a core balance current transformer at the circuit breaker or contactor. This current transformer has a current or turns ratio, which is independent of the ratios used by the transformers connected in the three-phase conductors. This is because a particular level of current is to be detected rather than a fraction or multiple of the stator load current. The switchgear manufacturer will normally recommend the ratio of the core balance transformer and the matching relay. The relay will be either instantaneous 50 N or an inverse time 51 N type depending upon whether the motor is controlled by a circuit breaker or a contactor.

A core balance current transformer functions more reliably and is more sensitive than a set of three current transformers connected in parallel. A three-transformer system is prone to responding to the initial inrush current of the motor. To avoid this the current setting needs to be higher than would be preferred.

The setting ranges of the relay are often given as 10% to 40% of nominal relay current with up to 0.5 second delay. Some designs have wider ranges of current and time settings.

Long motor feeder cables have enough capacitance to require a significant charging current. During some earth fault conditions the charging current is seen by the relay and so the relay setting should be made higher than the charging current. A reasonable upper margin is between 1.5 and 2.0 times the charging current.

12.7.5 Differential Stator Current

High voltage motors rated above a range of approximately 2 to 4 MW are usually provided with a Merz–Price differential current protection scheme. The range of kW ratings covers the requirements of many companies in the oil industry. The protection scheme is essentially the same as that applied to generators and large transformers. The instantaneous setting of the three-element (87) relay is typically in the range 10% to 40% of the nominal relay current for 1 amp circuits, see also sub-section 12.2.3 for generator protection.

12.7.6 Stalling Current

If the motor fails to run up to full speed during the starting period or is suddenly forced to run at a low or zero speed then the stator current will be at or near its starting value. This will cause overheating of the stator and rotor conductors and the much reduced cooling airflow will aggravate the problem. Protection is required to discriminate between a normal starting period and a stalling condition. Stalling is determined by checking that the current is at or near its stalling value and the tripping time is between the cold and hot thermal times for this current. Therefore the thermal image is used for this purpose, see Figure 12.18.

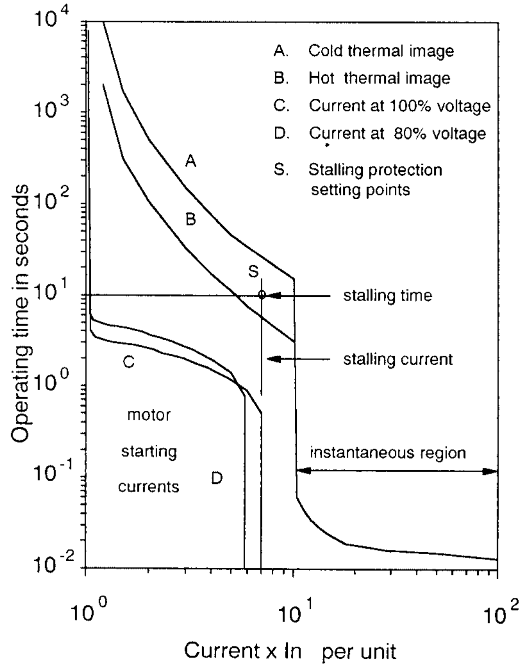

Figure 12.18 Motor run-up, thermal and instantaneous relay curves. The cold and hot thermal images of the relay are presented. The stalling conditions are indicated. The increase in the motor run-up time due to a reduction in terminal voltage is shown.

Should the stalling time be less than the corresponding cold thermal image time for the same stalling current then the relay will not detect the condition. Either the relay thermal settings will need to be reduced, if possible, or a separate special timing relay used instead.

12.7.7 Limitation to the Number of Successive Starts

Repeated starting of a motor in close succession will cause the accumulation of heat in the conductors and body of the motor. To safeguard against damage it is desirable to limit the number of starting attempts that are made in a predetermined time period. A well-specified motor will have a prescribed number of starting attempts, e.g. 2 to 5, and a rest period before the same attempts are repeated. The rest period is typically 0.5 to 1.0 hour. This should apply especially to motors that have long starting periods, such as motors that drive high-speed compressors.

Modern microcomputer based relays are easily able to provide this function.

12.7.8 Undercurrent

Most high voltage motors used in the oil industry operate at steady loads between 75% and 90% of their rated power capability. Should the motor suddenly find itself underloaded then it is possible that the driven machine has inadvertently lost its load, e.g. a pump loses liquid at its suction port. This may not present a problem to the motor but the driven machine could be damaged if it is allowed to operate continuously in this state.

Undercurrent protection is often specified as a back up to the process control systems. It has a typical setting range of 30% to 80% of the nominal relay current. A time delay is incorporated into the relay and its range is typically 2 to 120 seconds.

12.7.9 High Winding Temperature

Resistance temperature detectors e.g. 100 ohm platinum elements, or thermocouples are usually embedded in the three-stator phase windings to detect overheating in the vicinity of the conductors. A set of three is normally used, and a second set of three specified as spare detectors. The active elements are wired to a simple threshold relay that gives an alarm when the temperature is exceeded.

12.7.10 High Bearing Temperature

Similar detectors and relays as those in sub-section 12.7.9 are used to detect excessive temperature in the bearings of the motor. The relay gives an alarm when the temperature is exceeded.

12.7.11 Excessive Vibration

Excessive vibration in the shaft of a motor can be caused by several functions:

- Damaged rotor conductors.
- Damaged bearings, especially rolling element bearings.
- Low oil pressure in the bearings.
- Unbalance in the driven machine e.g. vane damage in a pump, blade damage in a compressor.
- Loose coupling or gearbox components.

The measurement of vibration should be made by a non-contacting transducer, i.e. it should not make direct contact with the rotating shaft.

12.8 LOW VOLTAGE INDUCTION MOTOR PROTECTION

In general a large amount of the theoretical aspects of the protection of high voltage motors applies to low voltage motors. However, some functions are not normally required, in particular, core balance earth faults (50 N and 51 N) see the note below:-

- Differential stator current (87).
- Undercurrent (37).
- High winding temperature.
- High bearing temperature.
- Excessive vibration.

Note: For small motors, e.g. 22 kW and below, the earth loop impedance including the feeder cable armouring may be too high. When this is the situation a risk of electric shock exists during a short circuit at or near to the motor. To reduce the exposure to the risk it is necessary to use a 51 N or a 50 N core balance current transformer and relay at the motor control centre. The choice of a 50 N is preferred subject to the contactor being properly coordinated with its upstream fuses.

Figure 12.19 shows the application of the above functions for a wide range of low voltage motor kW ratings.

Many modern installations favour the use of moulded case circuit breakers instead of fuses and separate relays. Moulded case circuit breakers are available with basic functions for small motors and more sophisticated functions for large motors.

12.8.1 Overloading or Thermal Image

It is common practice to use a bi-metal strip in each line of the protective device to create the thermal image of the low voltage motor. The protective device may be a moulded case circuit breaker or a time dependent relay. The thermal time constant of low voltage motors does not vary so widely as with high voltage motors. It is therefore reasonably easy to modify the shape of the thermal curves by changing the physical dimensions and properties of the bi-metal strip. The bi-metal strip is mechanically connected to the circuit breaker mechanism, or to an auxiliary switch in the case of a relay.

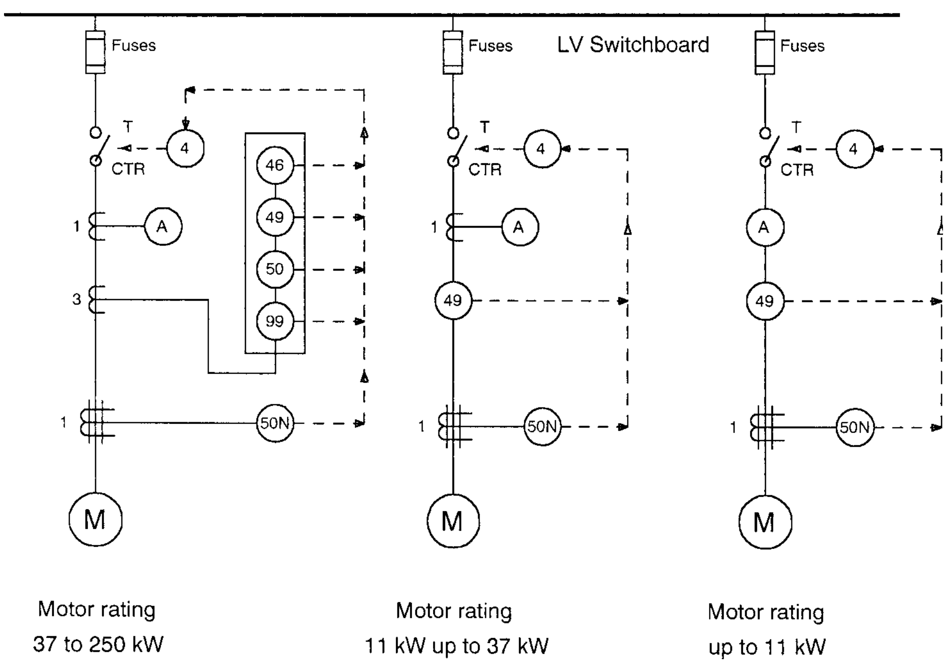

Figure 12.19 Protection devices for low voltage motors.

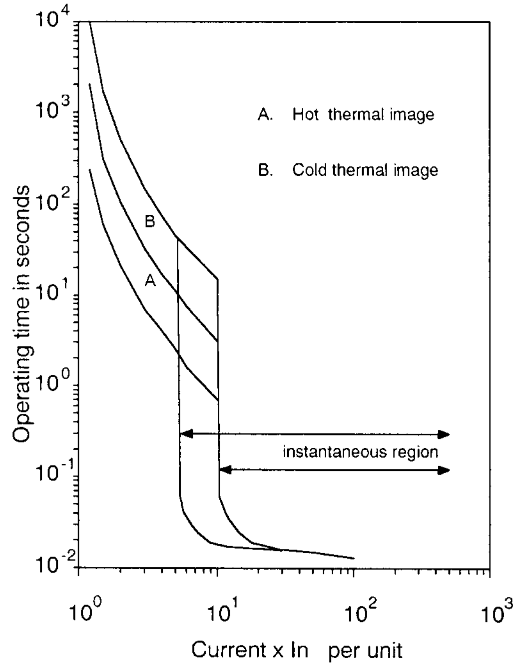

Figure 12.20 Thermal and instantaneous curves of a motor relay.

Hot and cold characteristics are usually available for circuit breakers having ratings from a few amps up to 500 amps. For a given frame size it is usually possible to fit different ratings of thermal elements. Each rating of a thermal element has a narrow or nominal current, see Figure 12.20.

12.8.2 Instantaneous or High-Set Overcurrent

The necessity for an instantaneous tripping function is the same as for a high voltage motor. This function can be provided by a magnetic repulsion device within the moulded case circuit breaker, by a (50) relay or by upstream fuses. If fuses are used then the contactor must be capable of carrying the I^2t duty until the fuse completes its function. To minimise the stressing of the contactor it should be coordinated with the fuses as recommended in IEC60947 Part 2, as a Type 2 requirement.

The range of settings for moulded case circuit breakers is typically between 5 and 30 times the nominal current. The lower values e.g. 5, 7.5 and 10 are often fixed for a particular circuit breaker, whilst the higher values are adjustable.

12.8.3 Negative Phase Sequence

The purpose of negative phase sequence protection is the same as for high voltage motors. It is not normally needed for motor ratings less than approximately 22 kW. In the simpler designs of moulded case circuit breakers and relays the negative phase sequence detection is more in the form of single-phase protection, wherein a phase is completely lost.

12.8.4 Core Balance Earth Fault

This function is occasionally required because the earth loop impedance is too high. Most of the impedance is in the armouring of the cable if the armouring is chosen to be braiding rather than wires. If the route length is short then the problem may not arise, but for good design practice it is not worth making exceptions for short routes. Core balance protection is normally required in these circumstances for motor ratings above approximately 18.5 kW. A core balance current transformer and a 50 N relay is used with a circuit breaker, or a 51 N relay with a contactor–fuse combination.

The sensitivity of the scheme should allow an earth fault current in the order of 30 mA to be detected and reliably tripped.

12.8.5 Stalling Current

Low voltage motors used in the oil industry usually have modest starting times, since the majority of their driven machines are pumps. Reciprocating compressors and ventilation fans can have reasonably long starting times. It is therefore not normally necessary to provide special relays to detect the stalling condition.

12.8.6 Limitation to the Number of Successive Starts

Low voltage motors are robust machines and can tolerate being restarted several times in succession. It is not normal practice to provide special facilities to limit the number of starts in a predetermined period of time. Modern motor control centres often have more sophisticated 'motor management' features than older equipment. It is reasonably easy to provide this requirement if the 'motor management' approach is adopted for the motor control centre.

12.9 LOW VOLTAGE STATIC LOAD PROTECTION

Static loads encompass heaters, battery chargers, uninterruptible power supplies, lighting distribution boards, socket outlets, cathodic protection, navigational aids, computers, public address, radio communication and the like. Excluded are loads that are not predominantly composed of motors. The load may have fractional kW motors for cooling fans.

They are essentially constant current loads that have a power factor near or equal to unity.

The protection required is usually kept as simple as possible, consisting of,

- Time-delayed overcurrent.
- Instantaneous or high-set overcurrent.
- Core balance earth fault.

The circuit may be controlled by a circuit breaker or a combination of a contactor and fuses. In some circuits that are controlled frequently as in the case of heaters controlled by thermostats or thermometers, the main protection may be incorporated into a circuit breaker whilst the control would be given by a contactor.

12.9.1 Time-delayed Overcurrent

A time-delayed overcurrent (51) relay would normally be used for a static load. The choice of the characteristic would depend to some extent on the nature of the load. A standard inverse characteristic would normally be adequate. Its pick-up current would be set at between 105% and 115% of the rated current of the load.

12.9.2 Instantaneous or High-Set Overcurrent

Instantaneous overcurrent protection would detect short circuits in the load and along its feeder cable. It would usually be practical to set the instantaneous elements of a moulded case circuit breaker to their lowest value e.g. five times the nominal current. If the protection is provided by a set of fuses then the fusing factor would be marginally above unity, the nearest fuse rating above the load current would be chosen. The protection must fully cover the I^2t capacity of the feeder cable.

12.9.3 Core Balance Earth Fault

The theoretical requirements for applying core balance earth fault protection are the same as those for low voltage motors. Some additional requirements often apply.

The requirement for a sensitivity of 30 mA should generally apply to final sub-circuits; see BS7671: 1992 Sections 412, 413 and 471 for further guidance.

In some situations the sensitivity may need to be reduced and a higher tripping current used e.g. 100 mA or 300 mA. Fluorescent lighting systems and welding socket feeders are subject to a poor quality of current waveform due to non-linear characteristics of their loads. The distortion superimposed on the fundamental current may be sufficient to cause spurious tripping of a fast-acting 30 mA relay.

12.10 MATHEMATICAL EQUATIONS FOR REPRESENTING STANDARD, VERY AND EXTREMELY INVERSE RELAYS

Since 1976 many relays have generally followed the recommendations of the IEC255-4, Clause 3.5.2, regarding the shape of their time–current curves. The general function recommended has the form:-

$$t = \frac{k}{\left(\frac{I^a}{I_n}\right) - u} \quad \text{seconds} \tag{12.1}$$

Where t = theoretical operating time, seconds.
I = relay current in pu or amps.
I_n = nominal current in pu or amps.
a = exponential constant.
k = constant for the particular relay.
u = constant for a particular relay determined from the time asymptote in the region of the rated current I_n. It usually has the value close to 1.0, in the range of 0.95 to 1.3. For

Table 12.1. The value of the exponent 'a' for different relay curves

Type	Range of a	Preferred value of a
Standard	0 to 0.5	0.02
Very	0.5 to 1.5	1.0
Extremely	greater than 1.5	2.0

negative phase sequence relays u has a value equal to K_2^2 where K_2 has the value between 0.02 and 0.2.

The three basic types, standard, very and extremely inverse, are approximately represented by three ranges in which the exponential constant (a) should fall:-

If the values of 'k' and 'a' are not known then a suitable curve can be fitted to a set of values taken from the manufacturer's published curves. In some cases the standard and thermal curves may require a modified function in order to give a good fit over a wide range of I/I$_n$. A suitable function for such purposes is:-

$$t = \frac{k_m}{\left(\dfrac{I^a}{I_n}\right) - k_b\left(\dfrac{I^b}{I_n}\right) - u} \quad \text{seconds}$$

Where k_m = modified form of k.

k_b = small auxiliary constant for the particular relay.

u = constant for a particular relay determined from the time asymptote in the region of the rated current I_n it usually has the value close to 1.0, in the range of 0.95 to 1.3. For negative phase sequence relays u has a value equal to K_2^2 where K_2 has the value between 0.02 and 0.2.

b = an auxiliary exponent to be formed by trial and error.

Note: This function is only applicable to currents 'within' the range of data used to determine the curve, and so it is important to include a pair of points at the largest per unit-current in the range.

From about 1975 to 1995 the various types of inverse curves were generated within the relays by electronic 'function generators'. Function generators are analogue devices that rely on the non-linear voltage-current characteristics of devices such as diodes, zener diodes and transistors. These are used in conjunction with analogue amplifiers and integrators to derive the required relay curves. Since the introduction of digital microelectronics the use of analogue methods has been gradually superseded. The curves produced by digital devices are more accurate, stable and repeatable. Almost any practical curve can be easily programmed into the microcomputer 'chips'. Hence the constant 'a' in equation (12.1) can be programmed as integers, 1, 2, 3, 4 etc. or as fractional values in between the integers e.g. 0.5, 1.1, 1.5.

By virtue of modern electronic techniques, especially microcomputer chips, it is possible to provide additional characteristics to inverse relays in particular. At the high multiples of current one or more instantaneous limits can be provided. These can be adjusted by the user to create a type

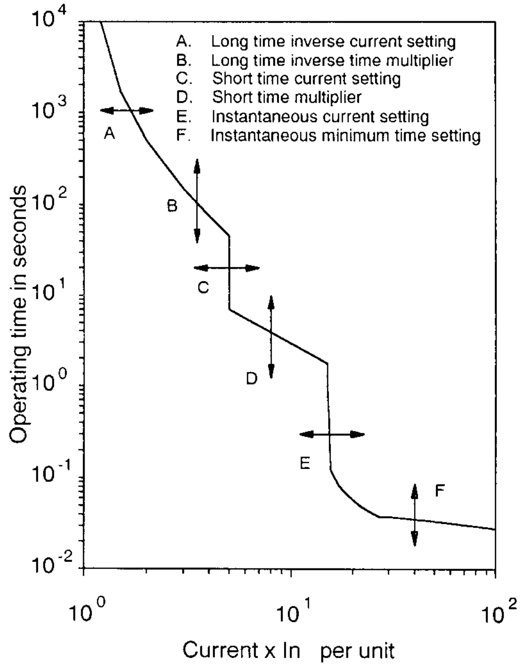

Figure 12.21 Operating time of a composite inverse time relay.

of staircase or stepped shape. Such additions are very useful in the coordination of incomer and interconnector relays at switchboards, with other devices downstream and upstream. The descriptions of these features occasionally vary between manufacturers, but generally they are called:

- Long delay setting, $\times I_n$
  or current plug setting
  symbol $I >$ (or I_1)
- Long delay time, seconds
  or time multiplier setting
  symbol $T(I >)$
- Short delay setting, $\times I_n$
  symbol $I \gg$ (or I_2)
- Short delay time, seconds
  symbol $T(I \gg)$
- Instantaneous or high-set setting, $\times I_n$
  symbol $I \gg$ or $I \ggg$ or (I_3)

Where I_n is the nominal current of the relay e.g. 1.0 per unit, 1 amp, 5 amps. Also the symbol I_o is used.

Note: The use of I_o, I_1 and I_2 should not be confused with their symmetrical component counterparts.

Some relays, for example as used with low voltage high current air circuit breakers and moulded case circuit breakers, have many adjustments to their parameters. Manufacturers often publish their curves showing the tolerances in the performance of their relays. These tolerances are shown as a band or range about a nominal curve. From a recent survey of relays and circuit breakers it was found that the tolerances and adjustments can be illustrated as shown in Figure 12.21.

Note: The characteristic between points A and B may be a horizontal line, a straight sloping line or an inverse curve.

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