

## . 19 . *A.C. Motor Protection*

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# • 19 • A.C. Motor Protection

## 19.1 INTRODUCTION

There are a wide range of a.c. motors and motor characteristics in existence, because of the numerous duties for which they are used. All motors need protection, but fortunately, the more fundamental problems affecting the choice of protection are independent of the type of motor and the type of load to which it is connected. There are some important differences between the protection of induction motors and synchronous motors, and these are fully dealt with in the appropriate section.

Motor characteristics must be carefully considered when applying protection; while this may be regarded as stating the obvious, it is emphasised because it applies more to motors than to other items of power system plant. For example, the starting and stalling currents/times must be known when applying overload protection, and furthermore the thermal withstand of the machine under balanced and unbalanced loading must be clearly defined.

The conditions for which motor protection is required can be divided into two broad categories: imposed external conditions and internal faults. Table 19.1 provides details of all likely faults that require protection.

External Faults	Internal faults
Unbalanced supplies	Bearing failures
Undervoltages	Winding faults
Single phasing	Overloads
Reverse phase sequence	

Table 19.1: Causes of motor failures

## 19.2 MODERN RELAY DESIGN

The design of a modern motor protection relay must be adequate to cater for the protection needs of any one of the vast range of motor designs in service, many of the designs having no permissible allowance for overloads. A relay offering comprehensive protection will have the following set of features:

- a. thermal protection
- b. extended start protection
- c. stalling protection

- d. number of starts limitation
- e. short circuit protection
- f. earth fault protection
- g. winding RTD measurement/trip
- h. negative sequence current detection
- i. undervoltage protection
- j. loss-of-load protection
- k. out-of-step protection
- l. loss of supply protection
- m. auxiliary supply supervision

(items k and l apply to synchronous motors only)

In addition, relays may offer options such as circuit breaker condition monitoring as an aid to maintenance. Manufacturers may also offer relays that implement a reduced functionality to that given above where less comprehensive protection is warranted (e.g. induction motors of low rating).

The following sections examine each of the possible failure modes of a motor and discuss how protection may be applied to detect that mode.

### 19.3 THERMAL (OVERLOAD) PROTECTION

The majority of winding failures are either indirectly or directly caused by overloading (either prolonged or cyclic), operation on unbalanced supply voltage, or single phasing, which all lead through excessive heating to the deterioration of the winding insulation until an electrical fault occurs. The generally accepted rule is that insulation life is halved for each 10° C rise in temperature above the rated value, modified by the length of time spent at the higher temperature. As an electrical machine has a relatively large heat storage capacity, it follows that infrequent overloads of short duration may not adversely affect the machine. However, sustained overloads of only a few percent may result in premature ageing and insulation failure.

Furthermore, the thermal withstand capability of the motor is affected by heating in the winding prior to a fault. It is therefore important that the relay characteristic takes account of the extremes of zero and full-load pre-fault current known respectively as the 'Cold' and 'Hot' conditions.

The variety of motor designs, diverse applications, variety of possible abnormal operating conditions and resulting modes of failure result in a complex thermal relationship. A generic mathematical model that is accurate is therefore impossible to create. However, it is possible to develop an approximate model if it is assumed that the motor is a homogeneous body, creating and dissipating

heat at a rate proportional to temperature rise. This is the principle behind the 'thermal replica' model of a motor used for overload protection.

The temperature  $T$  at any instant is given by:

$$T = T_{max} (1 - e^{-t/\tau})$$

where:

$T_{max}$  = final steady state temperature

$\tau$  = heating time constant

Temperature rise is proportional to the current squared:

$$T = KI_R^2 (1 - e^{-t/\tau})$$

where:

$I_R$  = current which, if flowing continuously, produces temperature  $T_{max}$  in the motor

Therefore, it can be shown that, for any overload current  $I$ , the permissible time  $t$  for this current to flow is:

$$t = \tau \log_e \left[ \frac{1}{\left\{ 1 - (I_R/I)^2 \right\}} \right]$$

In general, the supply to which a motor is connected may contain both positive and negative sequence components, and both components of current give rise to heating in the motor. Therefore, the thermal replica should take into account both of these components, a typical equation for the equivalent current being:

$$I_{eq} = \sqrt{(I_1^2 + KI_2^2)}$$

where

$I_1$  = positive sequence current

$I_2$  = negative sequence current

and

$$K = \frac{\text{negative sequence rotor resistance}}{\text{positive sequence rotor resistance}}$$

at rated speed. A typical value of  $K$  is 3.

Finally, the thermal replica model needs to take into account the fact that the motor will tend to cool down during periods of light load, and the initial state of the motor. The motor will have a cooling time constant,  $\tau_r$ , that defines the rate of cooling. Hence, the final thermal model can be expressed as:

$$t = \tau \log_e \left( \frac{k^2 - A^2}{k^2 - 1} \right) \dots \text{Equation 19.1}$$

where:

$$\tau = \text{heating time constant}$$

$$k = \frac{I_{eq}}{I_{th}}$$

$$A^2 = \text{initial state of motor (cold or hot)}$$

$$I_{th} = \text{thermal setting current}$$

Equation 19.1 takes into account the 'cold' and 'hot' characteristics defined in IEC 60255, part 8.

Some relays may use a dual slope characteristic for the heating time constant, and hence two values of the heating time constant are required. Switching between the two values takes place at a pre-defined motor current. This may be used to obtain better tripping performance during starting on motors that use a star-delta starter. During starting, the motor windings carry full line current, while in the 'run' condition, they carry only 57% of the current seen by the relay. Similarly, when the motor is disconnected from the supply, the heating time constant  $\tau$  is set equal to the cooling time constant  $\tau_r$ .

Since the relay should ideally be matched to the protected motor and be capable of close sustained overload protection, a wide range of relay adjustment is desirable together with good accuracy and low thermal overshoot.

Typical relay setting curves are shown in Figure 19.1.

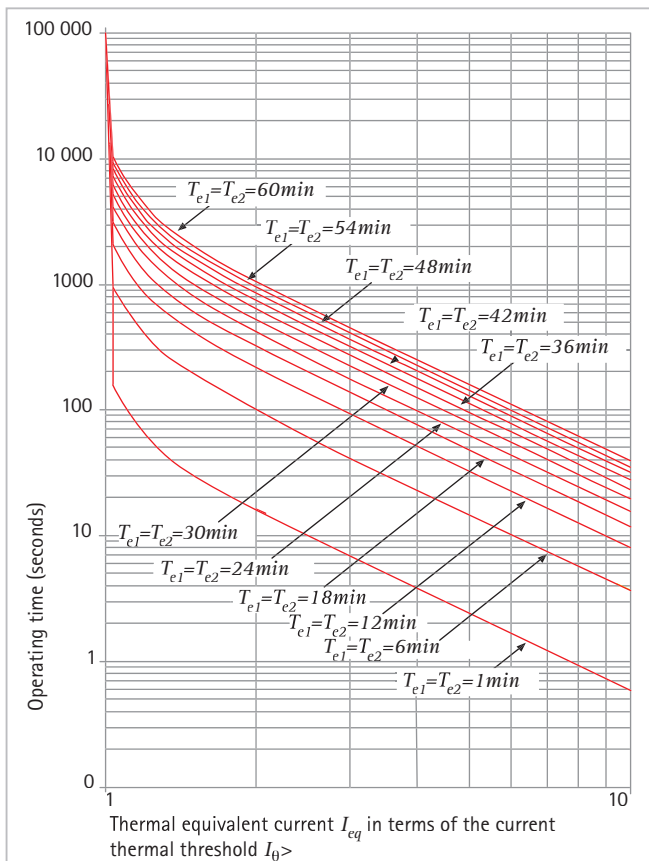


Figure 19.1: Thermal overload characteristic curves  
Cold curves. Initial thermal state 0%

## 19.4 START/STALL PROTECTION

When a motor is started, it draws a current well in excess of full load rating throughout the period that the motor takes to run-up to speed. While the motor starting current reduces somewhat as motor speed increases, it is normal in protection practice to assume that the motor current remains constant throughout the starting period. The starting current will vary depending on the design of the motor and method of starting. For motors started DOL (direct-on-line), the nominal starting current can be 4-8 times full-load current. However, when a star-delta starter is used, the line current will only be  $1/\sqrt{3}$  of the DOL starting current.

Should a motor stall whilst running, or fail to start, due to excessive loading, the motor will draw a current equal to its' locked rotor current. It is not therefore possible to distinguish between a stall condition and a healthy start solely on the basis of the current drawn. Discrimination between the two conditions must be made based on the duration of the current drawn. For motors where the starting time is less than the safe stall time of the motor, protection is easy to arrange.

However, where motors are used to drive high inertia loads, the stall withstand time can be less than the starting time. In these cases, an additional means must be provided to enable discrimination between the two conditions to be achieved.

### 19.4.1 Excessive Start Time/Locked Rotor Protection

A motor may fail to accelerate from rest for a number of reasons:

- loss of a supply phase
- mechanical problems
- low supply voltage
- excessive load torque

etc.

A large current will be drawn from the supply, and cause extremely high temperatures to be generated within the motor. This is made worse by the fact that the motor is not rotating, and hence no cooling due to rotation is available. Winding damage will occur very quickly – either to the stator or rotor windings depending on the thermal limitations of the particular design (motors are said to be stator or rotor limited in this respect). The method of protection varies depending on whether the starting time is less than or greater than the safe stall time. In both cases, initiation of the start may be sensed by detection of the closure of the switch in the motor feeder (contactor or CB) and optionally current rising above a starting current threshold value – typically

200% of motor rated current. For the case of both conditions being sensed, they may have to occur within a narrow aperture of time for a start to be recognised.

Special requirements may exist for certain types of motors installed in hazardous areas (e.g. motors with type of protection EEx 'e') and the setting of the relay must take these into account. Sometimes a permissive interlock for machine pressurisation (on EEx 'p' machines) may be required, and this can be conveniently achieved by use of a relay digital input and the in-built logic capabilities.

#### 19.4.1.1 Start time < safe stall time

Protection is achieved by use of a definite time overcurrent characteristic, the current setting being greater than full load current but less than the starting current of the machine. The time setting should be a little longer than the start time, but less than the permitted safe starting time of the motor. Figure 19.2 illustrates the principle of operation for a successful start.

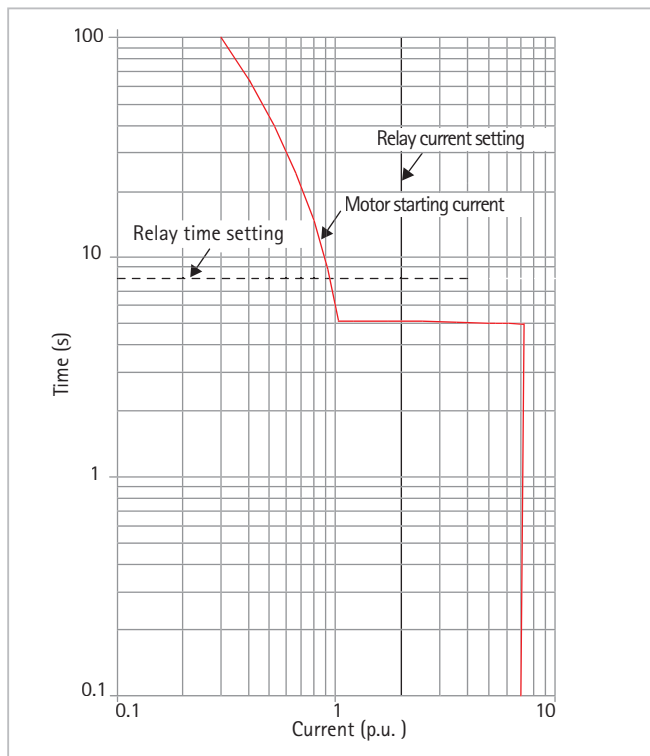


Figure 19.2: Motor start protection start time < safe stall time

#### 19.4.1.2 Start time => safe stall time

For this condition, a definite time overcurrent characteristic by itself is not sufficient, since the time delay required is longer than the maximum time that the motor can be allowed to carry starting current safely. An additional means of detection of rotor movement, indicating a safe start, is required. A speed-sensing switch usually provides this function. Detection of a

successful start is used to select relay timer used for the safe run up time. This time can be longer than the safe stall time, as there is both a (small) decrease in current drawn by the motor during the start and the rotor fans begin to improve cooling of the machine as it accelerates. If a start is sensed by the relay through monitoring current and/or start device closure, but the speed switch does not operate, the relay element uses the safe stall time setting to trip the motor before damage can occur. Figure 19.3(a) illustrates the principle of operation for a successful start, and Figure 19.3(b) for an unsuccessful start.

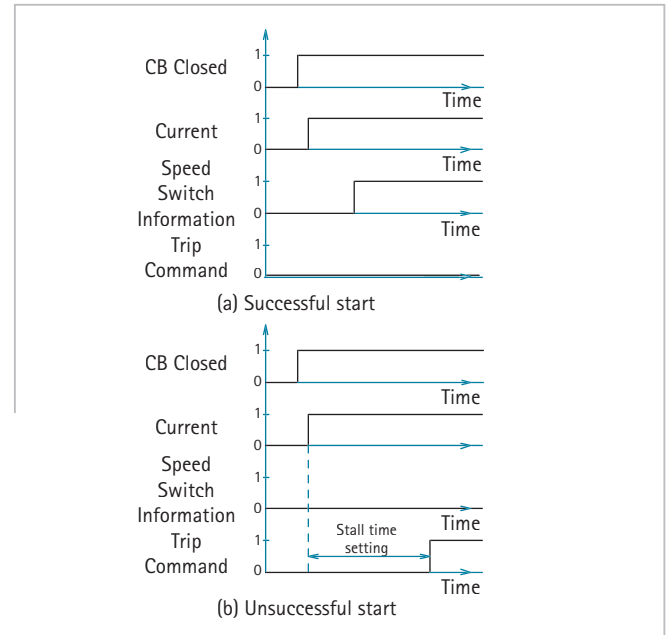


Figure 19.3: Motor start protection Start time > Safe stall time

#### 19.4.2 Stall Protection

Should a motor stall when running or be unable to start because of excessive load, it will draw a current from the supply equivalent to the locked rotor current. It is obviously desirable to avoid damage by disconnecting the machine as quickly as possible if this condition arises.

Motor stalling can be recognised by the motor current exceeding the start current threshold after a successful start – i.e. a motor start has been detected and the motor current has dropped below the start current threshold within the motor safe start time. A subsequent rise in motor current above the motor starting current threshold is then indicative of a stall condition, and tripping will occur if this condition persists for greater than the setting of the stall timer. An instantaneous overcurrent relay element provides protection.

In many systems, transient supply voltage loss (typically up to 2 seconds) does not result in tripping of designated motors. They are allowed to re-accelerate upon restoration of the supply. During re-acceleration, they

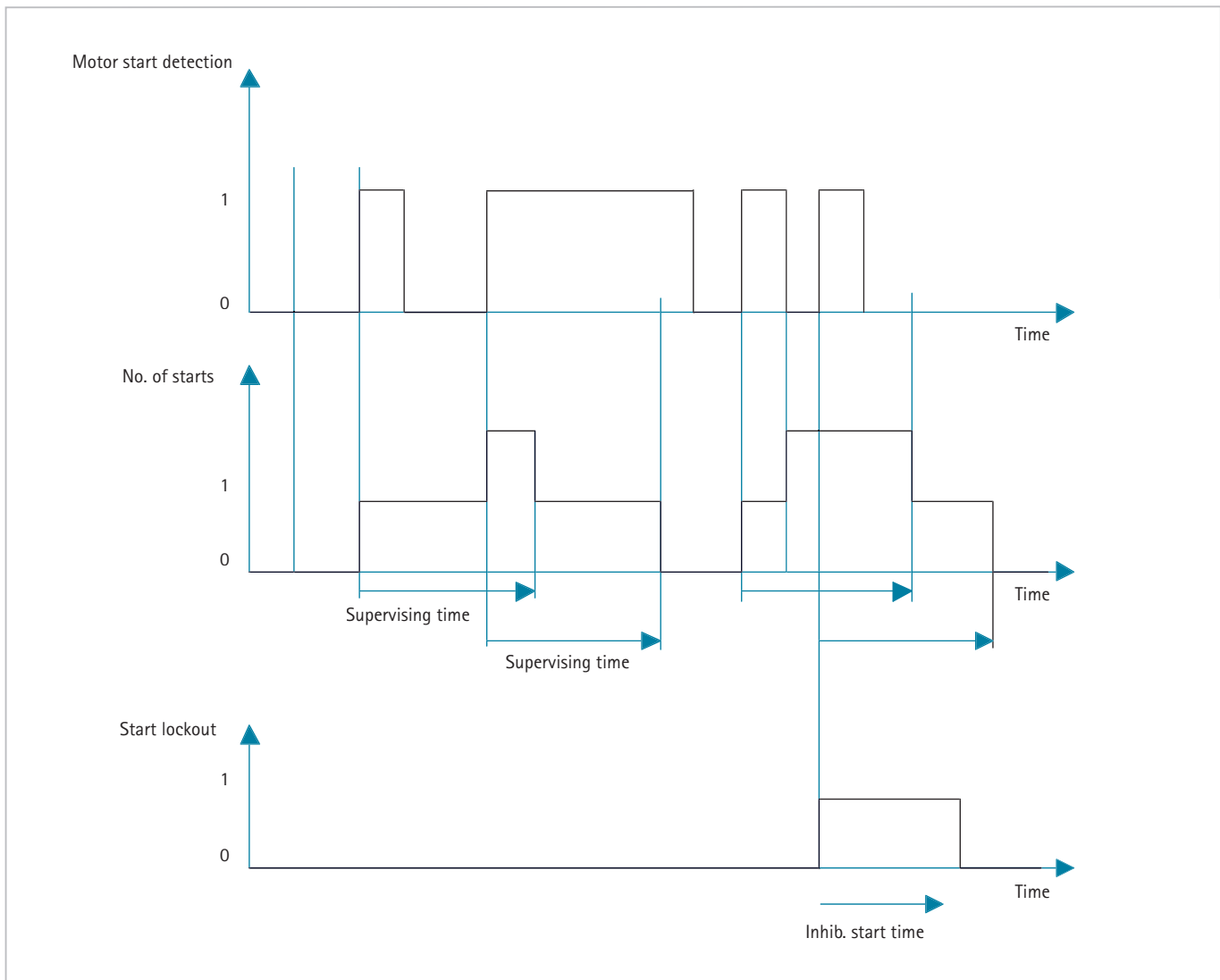


Figure 19.4: Start lockout information.

draw a current similar to the starting current for a period that may be several seconds. It is thus above the motor stall relay element current threshold. The stall protection would be expected to operate and defeat the object of the re-acceleration scheme.

A motor protection relay will therefore recognise the presence of a voltage dip and recovery, and inhibit stall protection for a defined period. The undervoltage protection element (Section 19.11) can be used to detect the presence of the voltage dip and inhibit stall protection for a set period after voltage recovery. Protection against stalled motors in case of an unsuccessful re-acceleration is therefore maintained.

The time delay setting is dependent on the re-acceleration scheme adopted and the characteristics of individual motors. It should be established after performing a transient stability study for the re-acceleration scheme proposed.

### 19.4.3 Number of Starts Limitation

Any motor has a restriction on the number of starts that are allowed in a defined period without the permitted winding, etc. temperatures being exceeded. Starting should be blocked if the permitted number of starts is exceeded. The situation is complicated by the fact the number of permitted 'hot' starts in a given period is less than the number of 'cold' starts, due to the differing initial temperatures of the motor. The relay must maintain a separate count of 'cold' and 'hot' starts. By making use of the data held in the motor thermal replica, 'hot' and 'cold' starts can be distinguished.

To allow the motor to cool down between starts, a time delay may be specified between consecutive starts (again distinguishing between 'hot' and 'cold' starts). The start inhibit is released after a time determined by the motor specification. The overall protection function is illustrated in Figure 19.4.

### 19.5 SHORT-CIRCUIT PROTECTION

Motor short-circuit protection is often provided to cater for major stator winding faults and terminal flashovers. Because of the relatively greater amount of insulation between phase windings, faults between phases seldom occur. As the stator windings are completely enclosed in grounded metal, the fault would very quickly involve earth, which would then operate the instantaneous earth fault protection. A single definite time overcurrent relay element is all that is required for this purpose, set to about 125% of motor starting current. The time delay is required to prevent spurious operation due to CT spill currents, and is typically set at 100ms. If the motor is fed from a fused contactor, co-ordination is required with the fuse, and this will probably involve use of a long time delay for the relay element. Since the object of the protection is to provide rapid fault clearance to minimise damage caused by the fault, the protection is effectively worthless in these circumstances. It is therefore only provided on motors fed via circuit breakers.

Differential (unit) protection may be provided on larger HV motors fed via circuit breakers to protect against phase-phase and phase-earth faults, particularly where the power system is resistance-earthed. Damage to the motor in case of a fault occurring is minimised, as the differential protection can be made quite sensitive and hence detects faults in their early stages. The normal definite time overcurrent protection would not be sufficiently sensitive, and sensitive earth fault protection may not be provided. The user may wish to avoid the detailed calculations required of capacitance current in order to set sensitive non-directional earth fault overcurrent protection correctly on HV systems (Chapter 9) or there may be no provision for a VT to allow application of directional sensitive earth fault protection. There is still a lower limit to the setting that can be applied, due to spill currents from CT saturation during starting, while on some motors, neutral current has been found to flow during starting, even with balanced supply voltages, that would cause the differential protection to operate. For details on the application of differential protection, refer to Chapter 10. However, non-directional earth fault overcurrent protection will normally be cheaper in cases where adequate sensitivity can be provided.

### 19.6 EARTH FAULT PROTECTION

One of the most common faults to occur on a motor is a stator winding fault. Whatever the initial form of the fault (phase-phase, etc.) or the cause (cyclic overheating, etc.), the presence of the surrounding metallic frame and casing will ensure that it rapidly develops into a fault involving earth. Therefore, provision of earth fault protection is very important. The type and sensitivity of protection provided depends largely on the system earthing, so the various types will be dealt with in turn.

It is common, however, to provide both instantaneous and time-delayed relay elements to cater for major and slowly developing faults.

#### 19.6.1 Solidly-Earthed System

Most LV systems fall into this category, for reasons of personnel safety. Two types of earth fault protection are commonly found – depending on the sensitivity required.

For applications where a sensitivity of > 20% of motor continuous rated current is acceptable, conventional earth fault protection using the residual CT connection of Figure 19.5 can be used. A lower limit is imposed on the setting by possible load unbalance and/or (for HV systems) system capacitive currents.

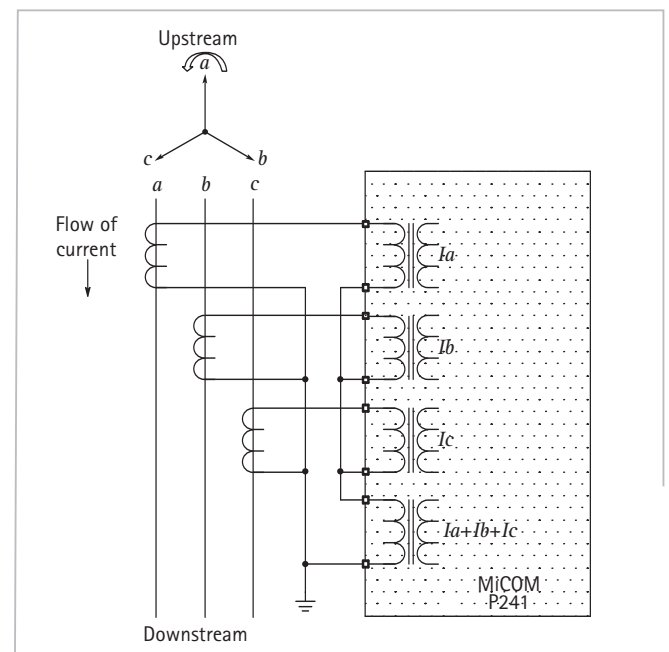


Figure 19.5: Residual CT connection for earth fault protection

Care must be taken to ensure that the relay does not operate from the spill current resulting from unequal CT saturation during motor starting, where the high currents involved will almost certainly saturate the motor CT's. It is common to use a stabilising resistor in series with the relay, with the value being calculated using the formula:

$$R_{stab} = \frac{I_{st}}{I_0} (R_{ct} + kR_l + R_r) \quad \dots \text{Equation 19.2}$$

where:

- $I_{st}$  = starting current referred to CT secondary
- $I_0$  = relay earth fault setting (A)
- $R_{stab}$  = stabilising resistor value (ohms)
- $R_{ct}$  = d.c. resistance of CT secondary (ohms)
- $R_l$  = CT single lead resistance (ohms)

- $k$  = CT connection factor  
 (= 1 for star pt at CT  
 = 2 for star pt at relay)
- $R_r$  = relay input resistance (ohms)

The effect of the stabilising resistor is to increase the effective setting of the relay under these conditions, and hence delay tripping. When a stabilising resistor is used, the tripping characteristic should normally be instantaneous. An alternative technique, avoiding the use of a stabilising resistor is to use a definite time delay characteristic. The time delay used will normally have to be found by trial and error, as it must be long enough to prevent maloperation during a motor start, but short enough to provide effective protection in case of a fault.

Co-ordination with other devices must also be considered. A common means of supplying a motor is via a fused contactor. The contactor itself is not capable of breaking fault current beyond a certain value, which will normally be below the maximum system fault current – reliance is placed on the fuse in these circumstances. As a trip command from the relay instructs the contactor to open, care must be taken to ensure that this does not occur until the fuse has had time to operate. Figure 19.6(a) illustrates incorrect grading of the relay with the fuse, the relay operating first for a range of fault currents in excess of the contactor breaking capacity. Figure 19.6(b) illustrates correct grading. To achieve this, it may require the use of an intentional definite time delay in the relay.

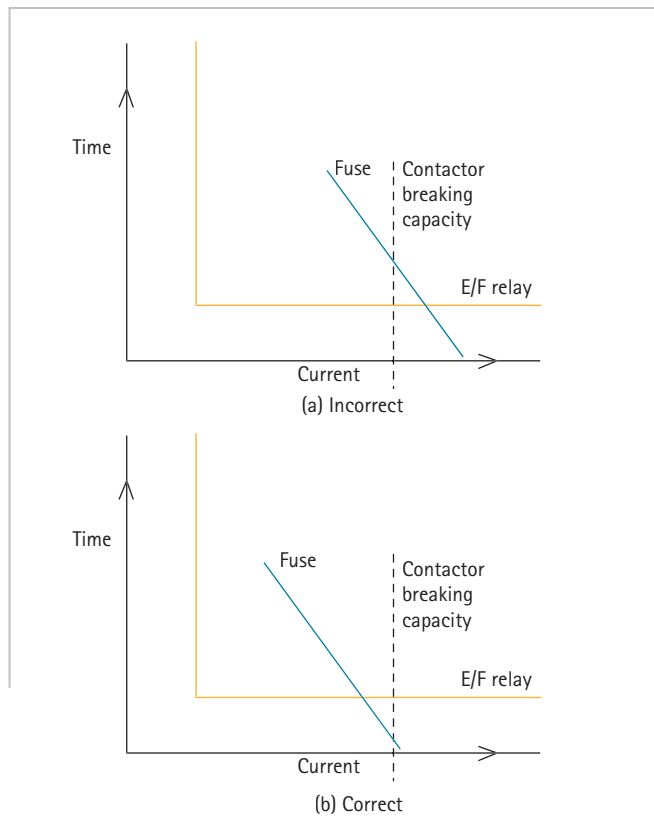


Figure 19.6: Grading of relay with fused contactor

If a more sensitive relay setting is required, it is necessary to use a core-balance CT. This is a ring type CT, through which all phases of the supply to the motor are passed, plus the neutral on a four-wire system. The turns ratio of the CT is no longer related to the normal line current expected to flow, so can be chosen to optimise the pick-up current required. Magnetising current requirements are also reduced, with only a single CT core to be magnetised instead of three, thus enabling low settings to be used. Figure 19.7 illustrates the application of a core-balance CT, including the routing of the cable sheath to ensure correct operation in case of core-sheath cable faults.

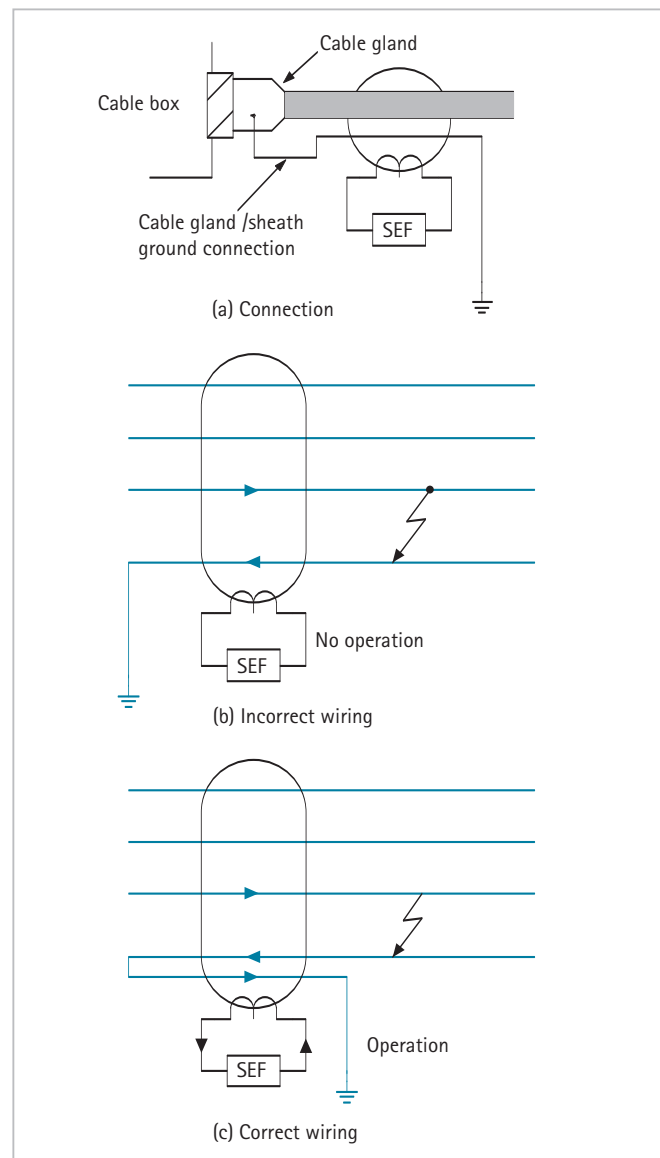


Figure 19.7: Application of core-balance CT

### 19.6.2 Resistance-Earthed Systems

These are commonly found on HV systems, where the intention is to limit damage caused by earth faults through limiting the earth fault current that can flow. Two methods of resistance earthing are commonly used:

19.6.2.1 Low resistance earthing

In this method, the value of resistance is chosen to limit the fault current to a few hundred amps – values of 200A-400A being typical. With a residual connection of line CT's, the minimum sensitivity possible is about 10% of CT rated primary current, due to the possibility of CT saturation during starting. For a core-balance CT, the

sensitivity that is possible using a simple non-directional earth fault relay element is limited to three times the steady-state charging current of the feeder. The setting should not be greater than about 30% of the minimum earth fault current expected. Other than this, the considerations in respect of settings and time delays are as for solidly earthed systems.

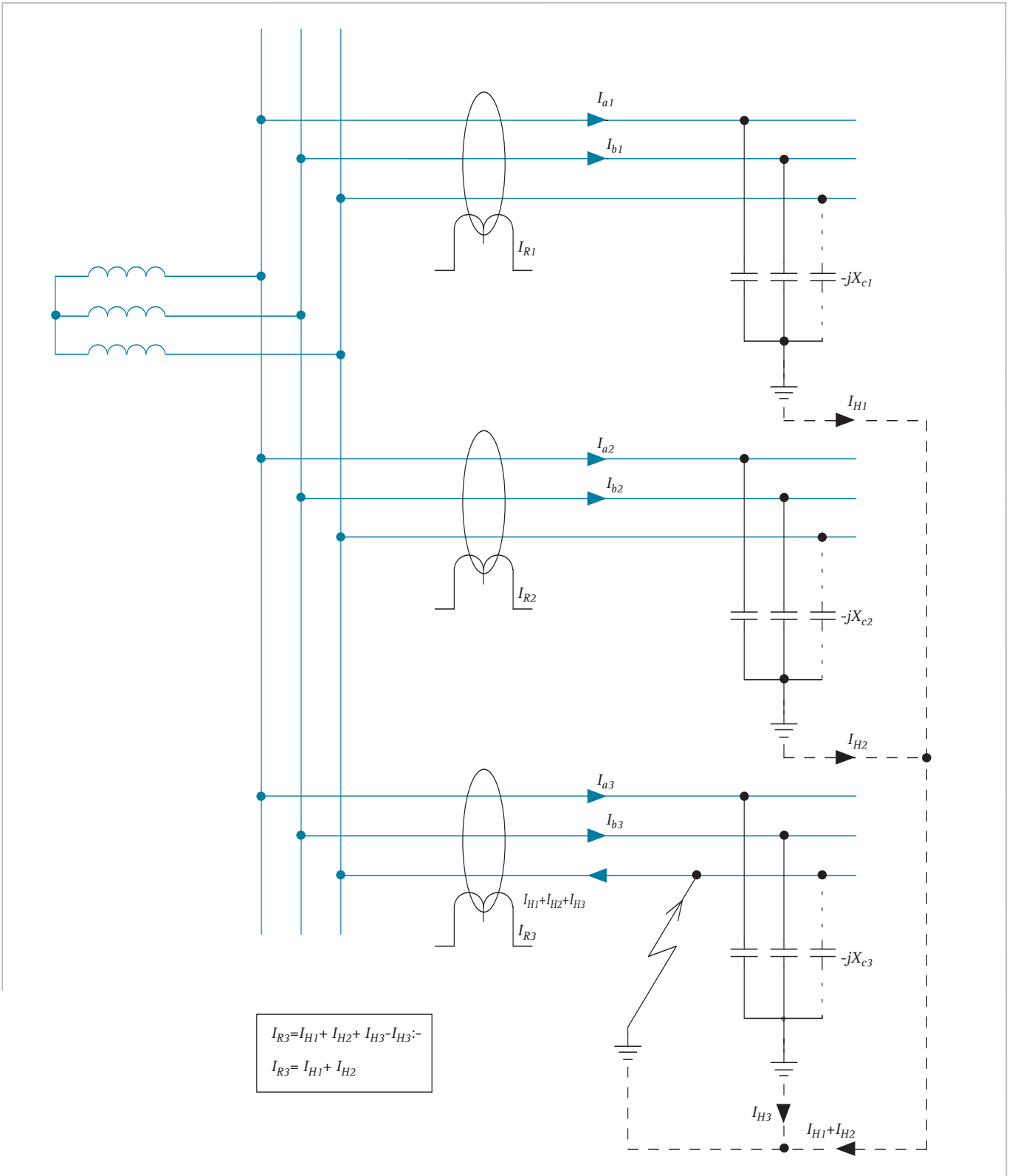


Figure 19.8: Current distribution in insulated-earth system for phase-earth fault

### 19.6.2.2 High resistance earthing

In some HV systems, high resistance earthing is used to limit the earth fault current to a few amps. In this case, the system capacitive charging current will normally prevent conventional sensitive earth fault protection being applied, as the magnitude of the charging current will be comparable with the earth fault current in the event of a fault. The solution is to use a sensitive directional earth fault relay. A core balance CT is used in conjunction with a VT measuring the residual voltage of the system, with a relay characteristic angle setting of  $+45^\circ$  (see Chapter 9 for details). The VT must be suitable for the relay and therefore the relay manufacturer should be consulted over suitable types – some relays require that the VT must be able to carry residual flux and this rules out use of a 3-limb, 3-phase VT. A setting of 125% of the single phase capacitive charging current for the whole system is possible using this method. The time delay used is not critical but must be fast enough to disconnect equipment rapidly in the event of a second earth fault occurring immediately after the first. Minimal damage is caused by the first fault, but the second effectively removes the current limiting resistance from the fault path leading to very large fault currents.

An alternative technique using residual voltage detection is also possible, and is described in the next section.

### 19.6.3 Insulated Earth System

Earth fault detection presents problems on these systems since no earth fault current flows for a single earth fault. However, detection is still essential as overvoltages occur on sound phases and it is necessary to locate and clear the fault before a second occurs. Two methods are possible, detection of the resulting unbalance in system charging currents and residual overvoltage.

#### 19.6.3.1 System charging current unbalance

Sensitive earth fault protection using a core-balance CT is required for this scheme. The principle is that detailed in Section 9.16.2, except that the voltage is phase shifted by  $+90^\circ$  instead of  $-90^\circ$ . To illustrate this, Figure 19.8 shows the current distribution in an Insulated system subjected to a C-phase to earth fault and Figure 19.9 the relay vector diagram for this condition. The residual current detected by the relay is the sum of the charging currents flowing in the healthy part of the system plus the healthy phase charging currents on the faulted feeder – i.e. three times the per phase charging current of the healthy part of the system. A relay setting of 30% of this value can be used to provide protection without the risk of a trip due to healthy system capacitive charging currents. As there is no earth fault current, it is also possible to set the relay at site after deliberately

applying earth faults at various parts of the system and measuring the resulting residual currents.

If it is possible to set the relay to a value between the charging current on the feeder being protected and the charging current for the rest of the system, the directional facility is not required and the VT can be dispensed with.

The comments made in earlier sections on grading with fused contactors also apply.

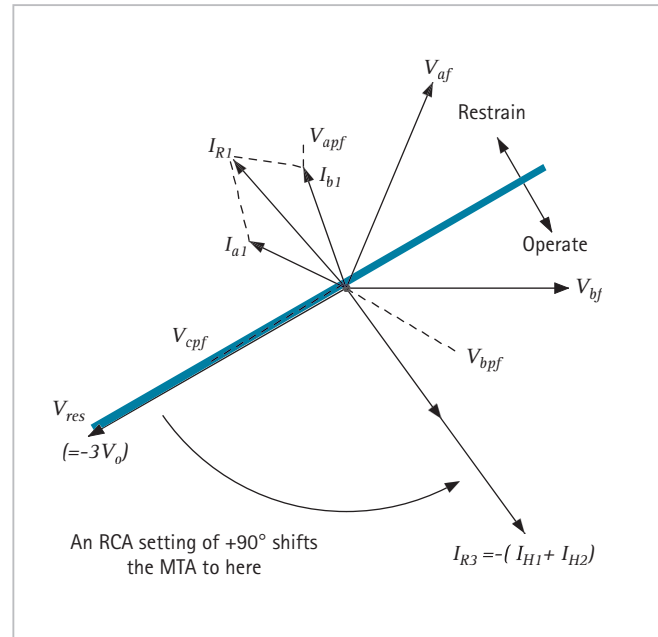


Figure 19.9: Relay vector diagram

#### 19.6.3.2 Residual voltage method

A single earth fault results in a rise in the voltage between system neutral and earth, which may be detected by a relay measuring the residual voltage of the system (normally zero for a perfectly balanced, healthy system). Thus, no CT's are required, and the technique may be useful where provision of an extensive number of core-balance CT's is impossible or difficult, due to physical constraints or on cost grounds. The VT's used must be suitable for the duty, thus 3-limb, 3-phase VT's are not suitable, and the relay usually has alarm and trip settings, each with adjustable time delays. The setting voltage must be calculated from knowledge of system earthing and impedances, an example for a resistance-earthed system is shown in Figure 19.10.

Grading of the relays must be carried out with care, as the residual voltage will be detected by all relays in the affected section of the system. Grading has to be carried out with this in mind, and will generally be on a time basis for providing alarms (1<sup>st</sup> stage), with a high set definite time trip second stage to provide backup.

### 19.6.4 Petersen Coil Earthed System

Earthing of a HV power system using a reactor equal to the system shunt capacitance is known as Petersen Coil (or resonant coil) earthing. With this method, a single earth fault results in zero earth fault current flowing (for perfect balance between the earthing inductance and system shunt capacitance), and hence the system can be run in this state for a substantial period of time while the fault is located and corrected. The detailed theory and protection method is explained in Section 9.17.

### 19.7 NEGATIVE PHASE SEQUENCE PROTECTION

Negative phase sequence current is generated from any unbalanced voltage condition, such as unbalanced

loading, loss of a single phase, or single-phase faults. The latter will normally be detected by earth fault protection, however, a fault location in a motor winding may not result in the earth fault protection operating unless it is of the sensitive variety.

The actual value of the negative sequence current depends on the degree of unbalance in the supply voltage and the ratio of the negative to the positive sequence impedance of the machine. The degree of unbalance depends on many factors, but the negative sequence impedance is more easily determined. Considering the classical induction motor equivalent circuit with magnetising impedance neglected of Figure 19.11:

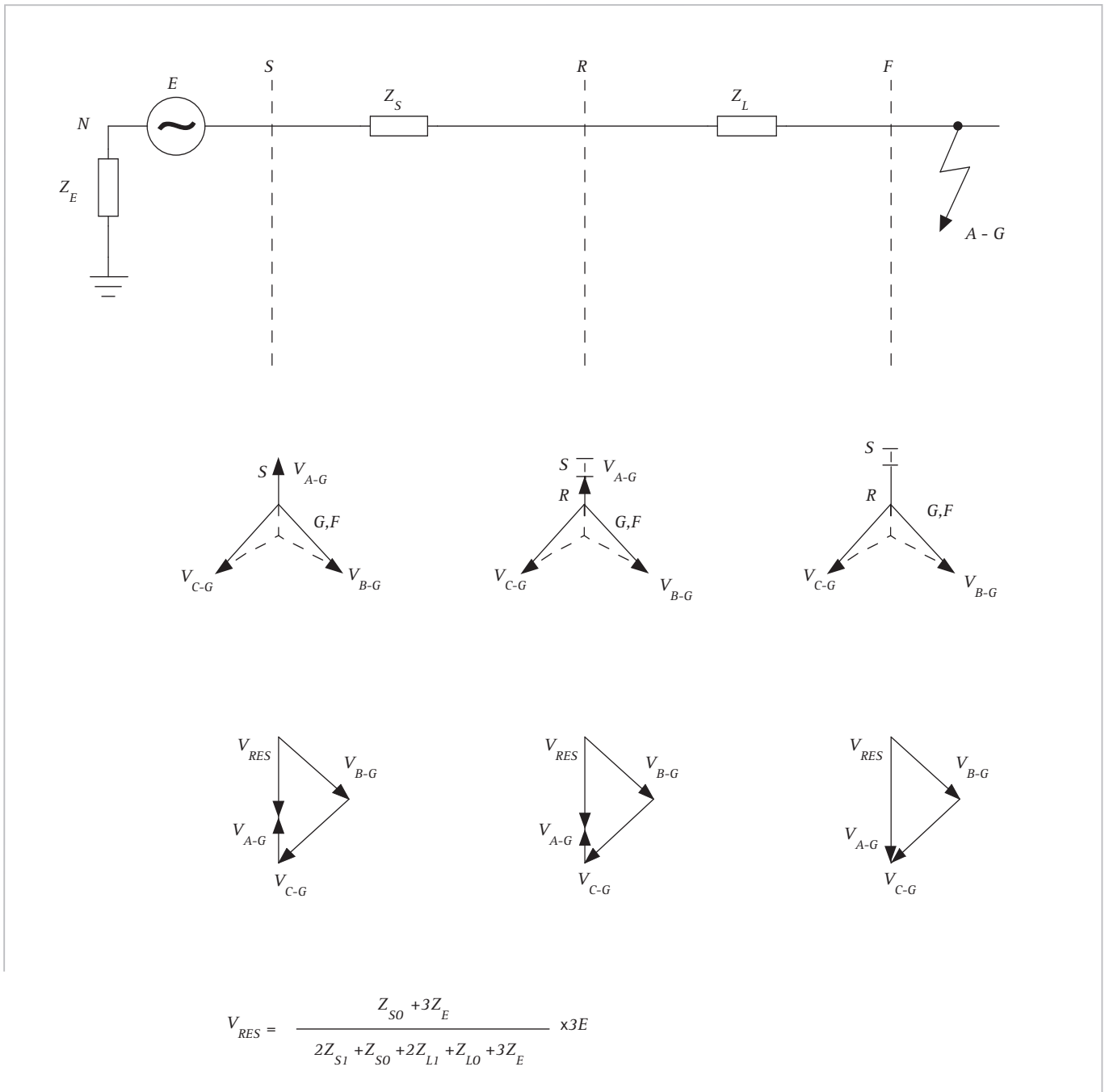


Figure 19.10: Residual voltage earth fault protection for resistance-earthed system.

Motor positive sequence impedance at slip  $s$

$$= \left[ \left( R_{1p} + R'_{2p} / (2 - s) \right)^2 + \left( X_{1p} + X'_{2p} \right)^2 \right]^{0.5}$$

Hence, at standstill ( $s=1.0$ ), impedance

$$= \left[ \left( R_{1p} + R'_{2p} \right)^2 + \left( X_{1p} + X'_{2p} \right)^2 \right]^{0.5}$$

The motor negative sequence impedance at slip  $s$

$$= \left[ \left( R_{1n} + R'_{2n} / s \right)^2 + \left( X_{1n} + X'_{2n} \right)^2 \right]^{0.5}$$

and, at normal running speed, the impedance

$$= \left[ \left( R_{1n} + R'_{2n} / 2 \right)^2 + \left( X_{1n} + X'_{2n} \right)^2 \right]^{0.5}$$

where:

suffix  $p$  indicates positive sequence quantities

and

suffix  $n$  indicates negative sequence quantities

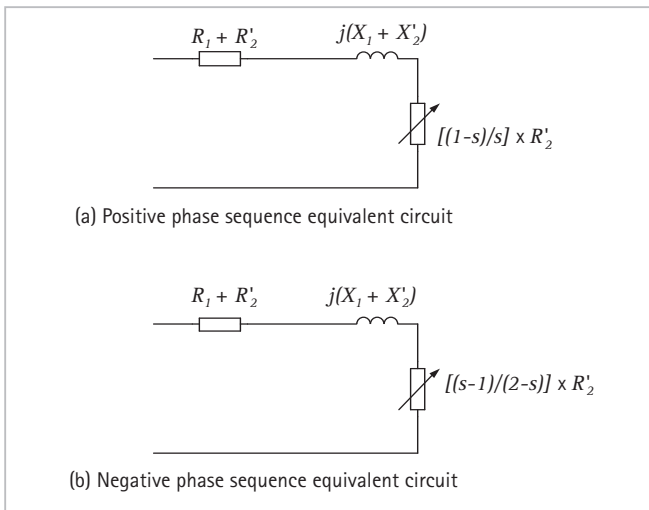


Figure 19.11: Induction motor equivalent circuit

Now, if resistance is neglected (justifiable as the resistance is small compared to the reactance), it can be seen that the negative sequence reactance at running speed is approximately equal to the positive sequence reactance at standstill. An alternative more meaningful way of expressing this is:

$$\frac{\text{positive seq. impedance}}{\text{negative seq. impedance}} = \frac{\text{starting current}}{\text{rated current}}$$

and it is noted that a typical LV motor starting current is  $6 \times \text{FLC}$ . Therefore, a 5% negative sequence voltage (due to, say, unbalanced loads on the system) would produce a 30% negative sequence current in the machine,

leading to excessive heating. For the same motor, negative sequence voltages in excess of 17% will result in a negative sequence current larger than rated full load current.

Negative sequence current is at twice supply frequency. Skin effect in the rotor means that the heating effect in the rotor of a given negative sequence current is larger than the same positive sequence current. Thus, negative sequence current may result in rapid heating of the motor. Larger motors are more susceptible in this respect, as the rotor resistance of such machines tends to be higher. Protection against negative sequence currents is therefore essential.

Modern motor protection relays have a negative sequence current measurement capability, in order to provide such protection. The level of negative sequence unbalance depends largely upon the type of fault. For loss of a single phase at start, the negative sequence current will be 50% of the normal starting current. It is more difficult to provide an estimate of the negative sequence current if loss of a phase occurs while running. This is because the impact on the motor may vary widely, from increased heating to stalling due to the reduced torque available.

A typical setting for negative sequence current protection must take into account the fact that the motor circuit protected by the relay may not be the source of the negative sequence current. Time should be allowed for the appropriate protection to clear the source of the negative sequence current without introducing risk of overheating to the motor being considered. This indicates a two stage tripping characteristic, similar in principle to overcurrent protection. A low-set definite time-delay element can be used to provide an alarm, with an IDMT element used to trip the motor in the case of higher levels of negative sequence current, such as loss-of-phase conditions at start, occurring. Typical settings might be 20% of CT rated primary current for the definite time element and 50% for the IDMT element. The IDMT time delay has to be chosen to protect the motor while, if possible, grading with other negative sequence relays on the system. Some relays may not incorporate two elements, in which case the single element should be set to protect the motor, with grading being a secondary consideration.

### 19.8 FAULTS IN ROTOR WINDINGS

On wound rotor machines, some degree of protection against faults in the rotor winding can be given by an instantaneous stator current overcurrent relay element. As the starting current is normally limited by resistance to a maximum of twice full load, the instantaneous unit can safely be set to about three times full load if a slight

time delay of approximately 30 milliseconds is incorporated. It should be noted that faults occurring in the rotor winding would not be detected by any differential protection applied to the stator.

### 19.9 RTD TEMPERATURE DETECTION

RTD's are used to measure temperatures of motor windings or shaft bearings. A rise in temperature may denote overloading of the machine, or the beginning of a fault in the affected part. A motor protection relay will therefore usually have the capability of accepting a number of RTD inputs and internal logic to initiate an alarm and/or trip when the temperature exceeds the appropriate setpoint(s). Occasionally, HV motors are fed via a unit transformer, and in these circumstances, some of the motor protection relay RTD inputs may be assigned to the transformer winding temperature RTD's, thus providing overtemperature protection for the transformer without the use of a separate relay.

### 19.10 BEARING FAILURES

There are two types of bearings to be considered: the anti-friction bearing (ball or roller), used mainly on small motors (up to around 350kW), and the sleeve bearing, used mainly on large motors.

The failure of ball or roller bearings usually occurs very quickly, causing the motor to come to a standstill as pieces of the damaged roller get entangled with the others. There is therefore very little chance that any relay operating from the input current can detect bearing failures of this type before the bearing is completely destroyed. Therefore, protection is limited to disconnecting the stalled motor rapidly to avoid consequential damage. Refer to Section 19.2 on stall protection for details of suitable protection.

Failure of a sleeve bearing can be detected by means of a rise in bearing temperature. The normal thermal overload relays cannot give protection to the bearing itself but will operate to protect the motor from excessive damage. Use of RTD temperature detection, as noted in Section 19.9, can provide suitable protection, allowing investigation into the cause of the bearing running hot prior to complete failure.

### 19.11 UNDERVOLTAGE PROTECTION

Motors may stall when subjected to prolonged undervoltage conditions. Transient undervoltages will generally allow a motor to recover when the voltage is restored, unless the supply is weak.

Motors fed by contactors have inherent undervoltage protection, unless a latched contactor is used. Where a specific undervoltage trip is required, a definite time undervoltage element is used. If two elements are provided, alarm and trip settings can be used. An interlock with the motor starter is required to block relay operation when the starting device is open, otherwise a start will never be permitted. The voltage and time delay settings will be system and motor dependent. They must allow for all voltage dips likely to occur on the system during transient faults, starting of motors, etc. to avoid spurious trips. As motor starting can result in a voltage depression to 80% of nominal, the voltage setting is likely to be below this value. Re-acceleration is normally possible for voltage dips lasting between 0.5-2 seconds, depending on system, motor and drive characteristics, and therefore the time delay will be set bearing these factors in mind.

### 19.12 LOSS-OF-LOAD PROTECTION

Loss-of-load protection has a number of possible functions. It can be used to protect a pump against becoming unprimed, or to stop a motor in case of a failure in a mechanical transmission (e.g. conveyor belt), or it can be used with synchronous motors to protect against loss-of-supply conditions. Implementation of the function is by a low forward power relay element, interlocked with the motor starting device to prevent operation when the motor is tripped and thus preventing a motor start. Where starting is against a very low load (e.g. a compressor), the function may also need to be inhibited for the duration of the start, to prevent maloperation.

The setting will be influenced by the function to be performed by the relay. A time delay may be required after pickup of the element to prevent operation during system transients. This is especially important for synchronous motor loss-of supply protection.

### 19.13 ADDITIONAL PROTECTION FOR SYNCHRONOUS MOTORS

The differences in construction and operational characteristics of synchronous motors mean that additional protection is required for these types of motor. This additional protection is discussed in the following sections.

#### 19.13.1 Out-of-Step Protection

A synchronous motor may decelerate and lose synchronism (fall out-of-step) if a mechanical overload exceeding the peak motor torque occurs. Other conditions that may cause this condition are a fall in the

applied voltage to stator or field windings. Such a fall may not need to be prolonged, a voltage dip of a few seconds may be all that is required. An out-of-step condition causes the motor to draw excessive current and generate a pulsating torque. Even if the cause is removed promptly, the motor will probably not recover synchronism, but eventually stall. Hence, it must be disconnected from the supply.

The current drawn during an out-of-step condition is at a very low power factor. Hence a relay element that responds to low power factor can be used to provide protection. The element must be inhibited during starting, when a similar low power factor condition occurs. This can conveniently be achieved by use of a definite time delay, set to a value slightly in excess of the motor start time.

The power factor setting will vary depending on the rated power factor of the motor. It would typically be 0.1 less than the motor rated power factor i.e. for a motor rated at 0.85 power factor, the setting would be 0.75.

### 19.13.2 Protection against Sudden Restoration of Supply

If the supply to a synchronous motor is interrupted, it is essential that the motor breaker be tripped as quickly as possible if there is any possibility of the supply being restored automatically or without the machine operator's knowledge.

This is necessary in order to prevent the supply being restored out of phase with the motor generated voltage.

Two methods are generally used to detect this condition, in order to cover different operating modes of the motor.

#### 19.13.2.1 Underfrequency protection

The underfrequency relay element will operate in the case of the supply failing when the motor is on load, which causes the motor to decelerate quickly. Typically, two elements are provided, for alarm and trip indications.

The underfrequency setting value needs to consider the power system characteristics. In some power systems, lengthy periods of operation at frequencies substantially below normal occur, and should not result in a motor trip. The minimum safe operating frequency of the motor under load conditions must therefore be determined, along with minimum system frequency.

#### 19.13.2.2 Low-forward-power protection

This can be applied in conjunction with a time delay to detect a loss-of-supply condition when the motor may share a busbar with other loads. The motor may attempt to supply the other loads with power from the stored kinetic energy of rotation.

A low forward power relay can detect this condition. See Section 19.12 for details. A time delay will be required to prevent operation during system transients leading to momentary reverse power flow in the motor.

## 19.14 MOTOR PROTECTION EXAMPLES

This section gives examples of the protection of HV and LV induction motors.

### 19.14.1 Protection of a HV Motor

Table 19.2 gives relevant parameters of a HV induction motor to be protected. Using a MiCOM P241 motor protection relay, the important protection settings are calculated in the following sections.

Quantity	Value
Rated output	1000kW CMR
Rated Voltage	3.3kV
Rated frequency	50Hz
Rated power factor/efficiency	0.9/0.92
Stall withstand time cold/hot	20/7s
Starting current	550% DOL
Permitted starts cold/hot	3/2
CT ratio	250/1
Start time@ 100% voltage	4s
Start time@ 80% voltage	5.5s
Heating/cooling time constant	25/75 min
System earthing	Solid
Control device	Circuit Breaker

Table 19.2: Motor data for example

#### 19.14.1.1 Thermal protection

The current setting  $I_{TH}$  is set equal to the motor full load current, as it is a CMR rated motor. Motor full load current can be calculated as 211A, therefore (in secondary quantities):

$$I_{TH} = \frac{211}{250} = 0.844$$

Use a value of 0.85, nearest available setting.

The relay has a parameter,  $K$ , to allow for the increased heating effect of negative sequence currents. In the absence of any specific information, use  $K=3$ .

Two thermal heating time constants are provided,  $\tau_1$  and  $\tau_2$ .  $\tau_2$  is used for starting methods other than DOL, otherwise it is set equal to  $\tau_1$ .  $\tau_1$  is set to the heating time constant, hence  $\tau_1=\tau_2=25mins$ . Cooling time constant  $\tau_r$  is set as a multiple of  $\tau_1$ . With a cooling time constant of 75mins,

$$\tau_r = 3 \times \tau_1$$

### 19.14.1.2 Short circuit protection

Following the recommendations of Section 19.5, with a starting current of 550% of full load current, the short-circuit element is set to  $1.25 \times 5.5 \times 211A = 1450A$ . In terms of the relay nominal current, the setting value is  $1450/250 = 5.8I_N$ .

There is a minimum time delay of 100ms for currents up to 120% of setting to allow for transient CT saturation during starting and 40ms above this current value. These settings are satisfactory.

### 19.14.1.3 earth fault protection

It is assumed that no CBCT is fitted. A typical setting of 30% of motor rated current is used, leading to an earth fault relay setting of  $0.3 \times 211/250 = 0.25I_N$ . A stabilising resistor is required, calculated in accordance with Equation 19.2 to prevent maloperation due to CT spill current during starting as the CT's may saturate. With the stabilising resistor present, instantaneous tripping is permitted.

The alternative is to omit the stabilising resistor and use a definite time delay in association with the earth fault element. However, the time delay must be found by trial and error during commissioning.

### 19.14.1.4 Locked rotor/Excessive start time protection

The current element must be set in excess of the rated current of the motor, but well below the starting current of the motor to ensure that a start condition is recognised (this could also be achieved by use of an auxiliary contact on the motor CB wired to the relay). A setting of 500A ( $2 \times I_N$ ) is suitable. The associated time delay needs to be set to longer than the start time, but less than the cold stall time. Use a value of 15s.

### 19.14.1.5 Stall protection

The same current setting as for locked rotor protection can be used – 500A. The time delay has to be less than the hot stall time of 7s but greater than the start time by a sufficient margin to avoid a spurious trip if the start time happens to be a little longer than anticipated. Use a value of 6.5s.

The protection characteristics for Sections 19.14.1.1–5 are shown in Figure 19.12.

### 19.14.1.6 Negative phase sequence protection

Two protection elements are provided, the first is definite time-delayed to provide an alarm. The second is an IDMT element used to trip the motor on high levels of negative sequence current, such as would occur on a loss of phase condition at starting.

In accordance with Section 19.7, use a setting of 20% with a time delay of 30s for the definite time element and 50% with a TMS of 1.0 for the IDMT element. The

resulting characteristic is shown in Figure 19.13. The motor thermal protection, as it utilises a negative sequence component, is used for protection of the motor at low levels of negative sequence current.

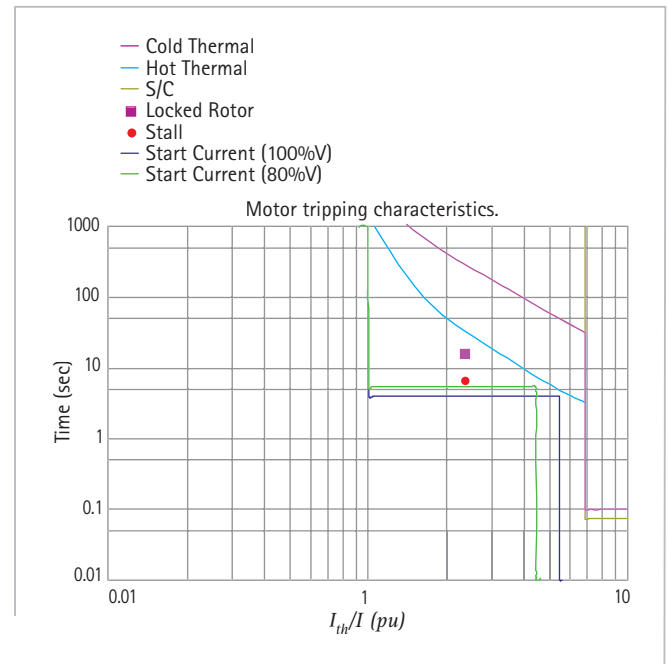


Figure 19.12: Protection characteristics for motor protection example

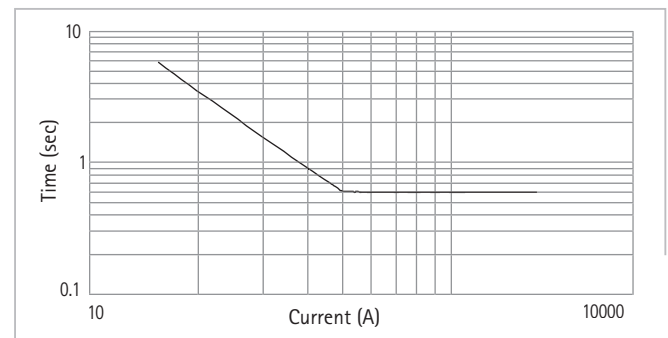


Figure 19.13: Motor protection example-negative sequence protection characteristic

### 19.14.1.7 Other protection considerations

If the relay can be supplied with a suitable voltage signal, stall protection can be inhibited during re-acceleration after a voltage dip using the undervoltage element (set to 80–85% of rated voltage). Undervoltage protection (set to approximately 80% voltage with a time delay of up to several seconds, dependent on system characteristics) and reverse phase protection can also be implemented to provide extra protection. Unless the drive is critical to the process, it is not justifiable to provide a VT specially to enable these features to be implemented.

### 19.14.2 Protection of an LV Motor

LV motors are commonly fed via fused contactors and therefore the tripping times of a protection relay for

overcurrent must be carefully co-ordinated with the fuse to ensure that the contactor does not attempt to break a current in excess of its rating. Table 19.3(a) gives details of an LV motor and associated fused contactor. A MiCOM P211 motor protection relay is used to provide the protection.

Parameter	Value	Unit
Standard	IEC 60034	
Motor Voltage	400	V
Motor kW	75	kW
Motor kVA	91.45	kVA
Motor FLC	132	A
Starting Current	670	%
Starting Time	4.5	s
Contactor rating	300	A
Contactor breaking capacity	650	A
Fuse rating	250	A

(a) LV motor example data

Parameter	Symbol	Value	Unit
Overcurrent		Disabled	-
Overload setting	$I_b$	4.4	A
Overload time delay	$I>t$	15	s
Unbalance	$I2$	20	%
Unbalance time delay	$I2>t$	25	s
Loss of phase time delay	$<I_p$	5	s

(b) Relay settings

Table 19.3: LV Motor protection setting example

#### 19.14.2.1 CT ratio

The relay is set in secondary quantities, and therefore a suitable CT ratio has to be calculated. From the relay manual, a CT with 5A secondary rating and a motor rated current in the range of 4–6A when referred to the secondary of CT is required. Use of a 150/5A CT gives a motor rated current of 4.4A when referred to the CT secondary, so use this CT ratio.

#### 19.14.2.2 Overcurrent (short-circuit) protection

The fuse provides the motor overcurrent protection, as the protection relay cannot be allowed to trip the contactor on overcurrent in case the current to be broken exceeds the contactor breaking capacity. The facility for overcurrent protection within the relay is therefore disabled.

#### 19.14.2.3 Thermal (overload) protection

The motor is an existing one, and no data exists for it except the standard data provided in the manufacturers catalogue. This data does not include the thermal (heating) time constant of the motor.

In these circumstances, it is usual to set the thermal protection so that it lies just above the motor starting current.

The current setting of the relay,  $I_b$ , is found using the formula

$$I_b = 5 \times I_n / I_p$$

where

$$I_n = \text{motor rated primary current}$$

$$I_p = \text{CT primary current}$$

$$\text{Hence, } I_b = 5 \times 132 / 150 = 4.4\text{A}$$

With a motor starting current of 670% of nominal, a setting of the relay thermal time constant with motor initial thermal state of 50% of 15s is found satisfactory, as shown in Figure 19.14.

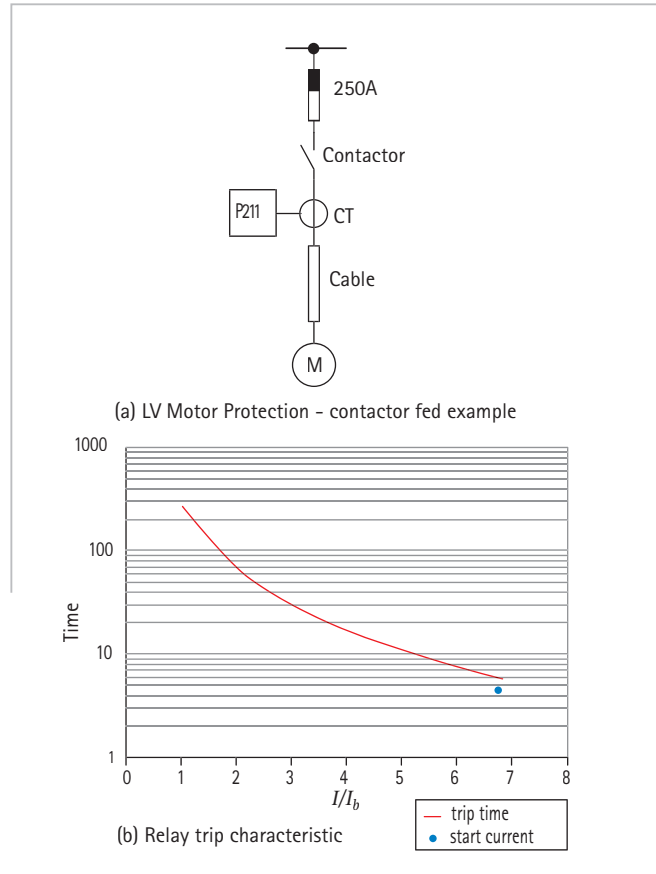


Figure 19.14: Motor protection example - contactor-fed motor

#### 19.14.2.4 Negative sequence

#### (phase unbalance) protection

The motor is built to IEC standards, which permit a negative sequence (unbalance) voltage of 1% on a continuous basis. This would lead to approximately 7% negative sequence current in the motor (Section 19.7). As the relay is fitted only with a definite time relay element, a setting of 20% (from Section 19.7) is appropriate, with a time delay of 25s to allow for short high-level negative sequence transients arising from other causes.

#### 19.14.2.5 Loss of phase protection

The relay has a separate element for this protection. Loss of a phase gives rise to large negative sequence currents, and therefore a much shorter time delay is required. A definite time delay of 5s is considered appropriate. The relay settings are summarised in Table 19.3(b).