C9

A.C. Motor Protection

Network Protection & Automation Guide

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Chapter C9

A.C. Motor Protection

C9

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 C9.1 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 C9.1:
Causes of motor failures

2. Modern relay design

The design of a 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

Note: *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.

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

τ = heating time constant

Temperature rise is proportional to the current squared:

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

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:

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

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:

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

where

I_1 = positive sequence current

I_2 = negative sequence current

$$K = \frac{\textit{negative sequence rotor resistance}}{\textit{positive sequence rotor resistance}}$$ at rated speed.

For an asynchronous motor, K can be estimated with the following formula:

$$K=2\frac{T_s/T_n}{S_n\,(I_s/I_n)^2}-1$$

Where

T_s : starting torque

T_n : rated torque

I_s : starting current

I_n : rated current

Normally K is within the range 2 to 9, according to motor data sheet. It is generally a setting of the thermal overload protection. 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, τ_r , that defines the rate of cooling. Hence, the final thermal model can be expressed as:

$$t = \tau \log_e \left(k^2 - A^2\right) \Big/ \left(k^2 - 1\right)$$ ...Equation C9.1

where:

τ = heating time constant

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

A^2 = initial state of motor (cold or hot) in percentage of the thermal state

If the initial thermal state is due to a constant load current I_L, the A^2 factor can be computed by the equation $A^2=(I_L= I_{th})^2$

I_{th} = thermal setting current

Equation C9.1 takes into account the 'cold' and 'hot' characteristics defined in IEC 60255 -149.

3. Thermal (overload) protection

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 τ is set equal to the cooling time constant τ_r.

Most of motors are designed to operate at a maximum ambient temperature of 40°C. This value is defined in motor datasheet, as the rated ambient temperature, used to defined the thermal withstand (cold and hot curves).

The real operating ambient temperature could be less (e.g. motor in caves) or more than the rated value. Most of thermal relays proposed to connect an ambient temperature sensor (e.g. with RTDs sensors), and this temperature is taken into account in the thermal level estimation. The calculated heat rise value could be increased or decreased when the temperature is above or below the rated value. As defined in the IEC60255-151, the motor thermal level is compensated by a factor Fa, defined by the following equation:

$$F_a = \frac{T_{max} - T_{limit}}{T_{max} - T_a}$$

Where

T_{max} is the motor maximum temperature

T_a is the actual ambient temperature of the motor

T_{limit} is the ambient temperature design limits for operation at rated load without causing thermal degradation of insulation, typically 40°C

When temperature sensor is not available, a user setting could be provided to adjust the ambient temperature, when it is different from typical value (40°C).

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 C9.1.

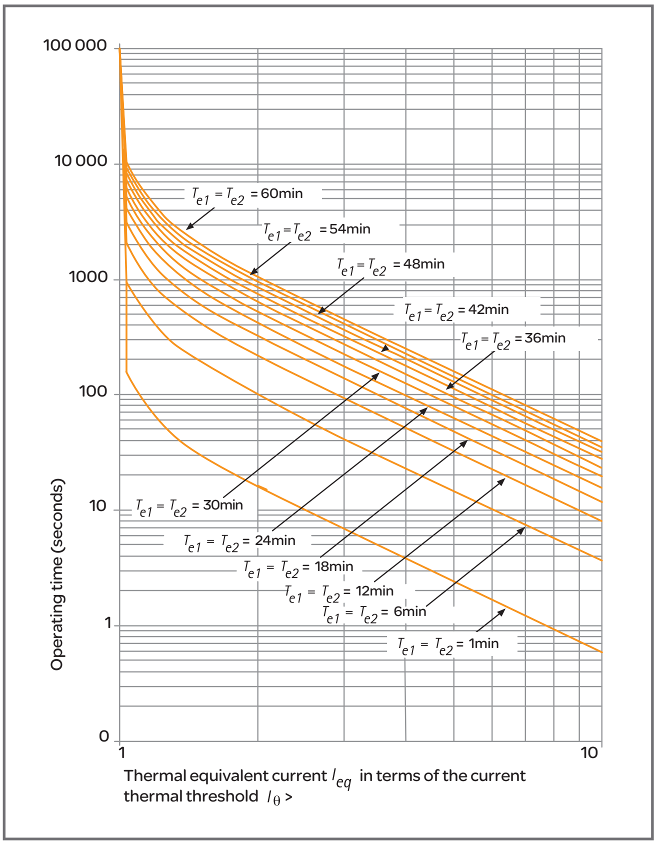

Figure C9.1:
Thermal overload characteristic curves.
Cold curves. Initial thermal state 0%

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. The motor starting current reduces somewhat as motor speed increases. 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 √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

4. Start/stall protection

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.

4.1 Excessive start time/locked rotor protection

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

a. loss of a supply phase

b. mechanical problems

c. low supply voltage

d. 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, from the motor standstill status, the 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.

4.1.1 Start time < safe stall time

In the majority of cases the starting time of a normal induction motor is less than the maximum stall withstand time. Under this condition it is possible to discriminate on a time basis between the two conditions and thus provide protection against stalling.

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 maximum stall withstand time. Generally, the time setting should be set 1 or 2 seconds above the start time. Figure C9.2 illustrates the principle of operation for a successful start.

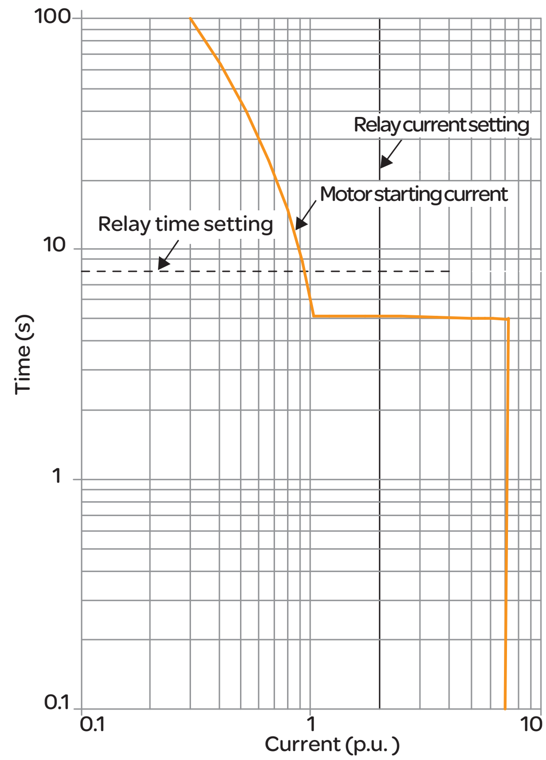

Figure C9.2:
Motor start protection start time < safe stall time

4.1.2 Start time => safe stall time

Where motors are used to drive high inertia loads, the stall withstand time can be less than the starting 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 stalling 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 the 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 C9.3(a) illustrates the principle of operation for a successful start, and Figure C9.3(b) for an unsuccessful start.

4. Start/stall protection

Normally the speed sensor indicates motor start or not. Alternatively, some motor protection relays can distinguish start and stall without external speed information. Such a relay estimates the motor slip based on the calculation of the positive sequence resistance of the machine.

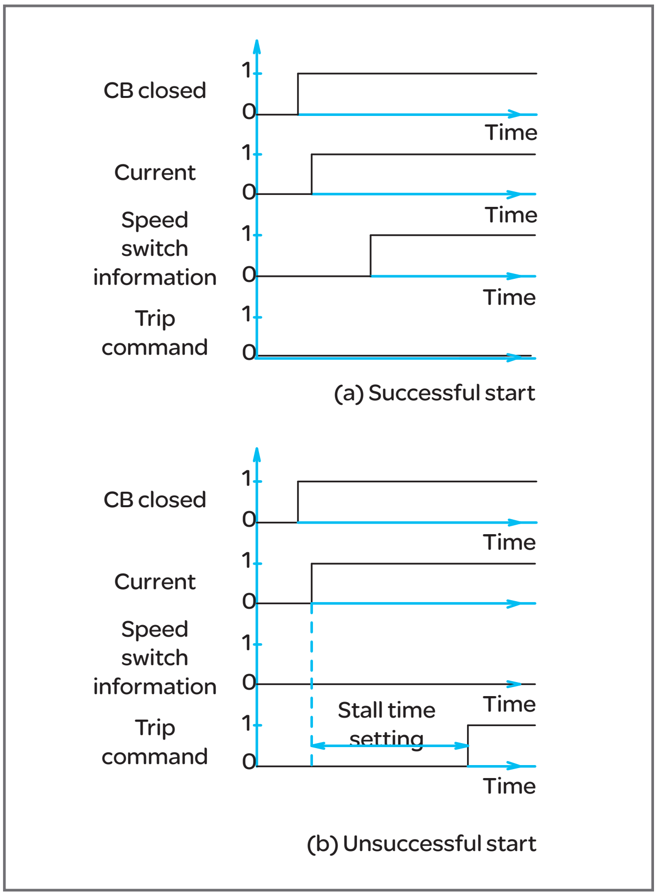

Figure C9.3:
Relay settings for start time> stall time

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.

4.3 Re-acceleration

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 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 if the allowable stall time is less than the re-acceleration time.

The undervoltage protection element can be used to detect the presence of the voltage dip and voltage recovery. If, on recovery of the voltage, the current exceeds the stalling current threshold within a definite time such as 5 seconds, then the re-acceleration is recognised. In that case, the re-acceleration timer replaces the stall timer, as shown in Figure C9.4. If the current falls below the stalling current threshold before the end of the expired of the re-acceleration timer, the re-acceleration is successful; otherwise the relay issues a trip signal.

This function is disabled during the starting period.

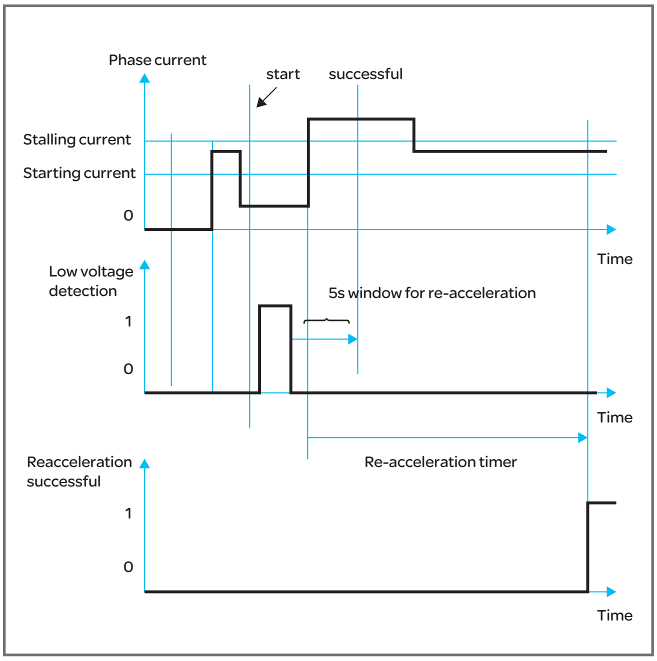

Figure C9.4:
Motor re-acceleration

4.4 Number of starts limitation

Any motor has a restriction on the number of starts that are allowed in a defined period to ensure that the thermal limit of the motor is not exceeded and to limit any mechanical impact from too many starts.

4. Start/stall protection

If the permitted number of starts in a given supervising period is reached, starting should be blocked for the remaining time of that supervising period or the defined start inhibit time which is greater, as shown in Figure C9.5 and Figure C9.6.

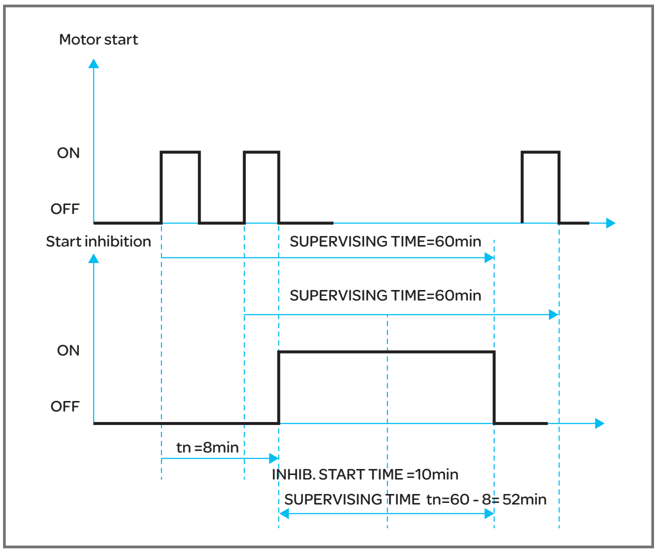

Figure C9.5:
Motor start inhibition (a)

In these two figures, the maximum number of starts is 2. Figure C9.5 shows the situation where two starts have occurred within 8 minutes. As the supervision time is set to 60 minutes no further starts are permitted for 52 minutes even if the Inhibit start time expires.

In Figure C9.6 two starts occur within 55 minutes. Without the Inhibit timer a new supervision period would start in 5 minutes and permit a new start however as the Inhibit timer is set to 10 minutes, starting is blocked until this expires (a further 5 minutes later).

The situation is complicated by the fact the number of permitted 'hot' starts in a given supervising 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.

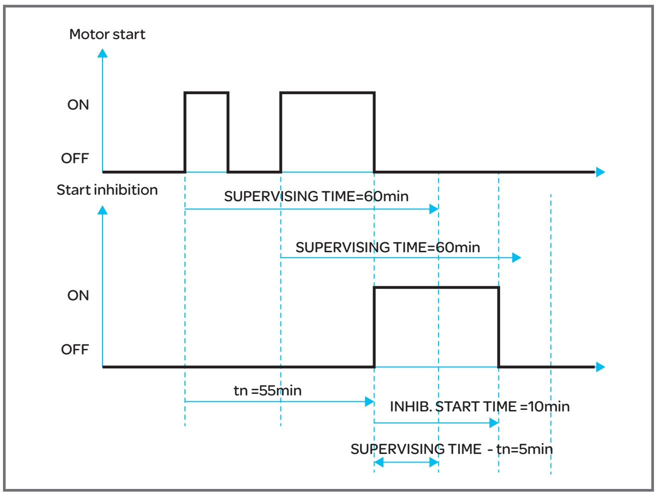

Figure C9.6:
Motor start inhibition (b)

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.

5.1 Motor differential protection

The over current protection is usually applied for the motor stator winding faults. However the sensitivity of the over current protection declines when the motor capacity increases. So when the motor capacity is more than 2000KW or the over current protection is not sufficiently sensitive, it is necessary to apply differential protection on larger motors via circuit breakers to protect against phase-phase and single phase earth faults. Damage to the motor in case of a fault is minimised, as the differential protection can be made quite sensitive and hence detecting faults in their early stages.

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5. Short circuit protection

For details on the conventional differential protection (both biased differential protection and the high impedance differential protection), refer to the section "Differential Protection of Direct Connected Generators" on chapter "Generator and Generator-Transformer Protection".

The reliability of conventional differential protection relies on the current transformer saturation characteristic, current transformer's secondary burden and so on. As explained in previous chapters, it is almost impossible that the two current transformers have the same transient characteristics during high current events such as motor starting. It is possible that the differential protection trips incorrectly under an external fault condition for similar reasons. So the settings for conventional bias differential protection cannot be very small or additional restraint elements (such as CT saturation detection) must be provided to ensure stability in all conditions.

5.2 Self balance differential protection

An alternative is to apply self balance winding differential protection. It is also named as magnetic balanced differential protection, as shown in Figure C9.7. Three core balance current transformers are applied in the self balance winding differential protection. As with the more conventional approach to differential protection both ends of the windings must be accessible at the motor terminals.

Both ends of each phase winding pass through the current transformer in different directions. The conductors shall be placed reasonably concentric within the window of the core balance current transformers to keep the spill current to a minimum.

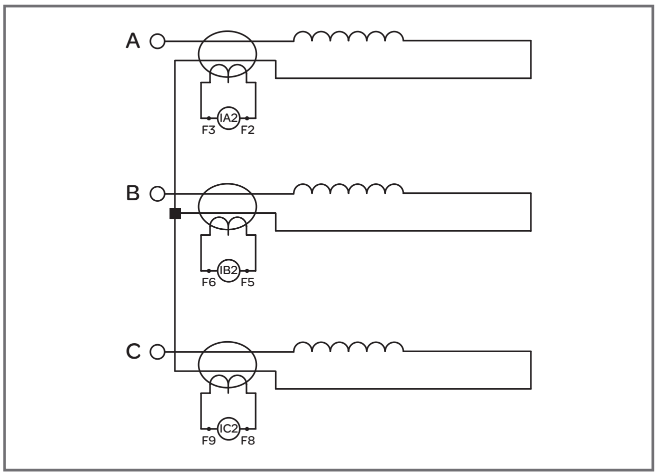

Figure C9.7:
Self balance winding differential protection

So under the normal condition, the magnetic flux and the secondary current shall be very small. When there are phase-phase or single phase earth faults within the stator windings, the magnetic balance is broken and there are secondary currents which will trigger the relay operation.

Unlike the other protection applications, here the current transformers are normally installed very near the motor output terminal to avoid long cabling. So it only protects the motor and does not include the longer cables between motor and the control switchgear.

5.2.1 Settings

In this section, it takes the unearthed system as example to introduce the setting rule for self balance differential protection.

In the normal condition, the unbalance current from the core balance current transformer is very small. The unbalance current is due to the capacitive current of the motor (I'cm) not including the capacitive current of the cable from motor to control switchgear.

The current setting for self balance winding differential protection shall be larger than the maximum capacitive current of the motor when there are external faults on the other feeds or equipment, as shown in Figure C9.8. Compared with the normal condition, the capacitive current will increase by a maximum √3 due to the increase of the phase voltage under the external single phase earth fault. Due to the relatively low value of this capacitive current the protection current setting can be very small and the sensitivity is high. The capacitive currents of the overall system under the distribution transformer return to the system via the fault point, as shown in Figure C9.9. The unbalance current of the core balance current transformer is the overall system capacitive current.

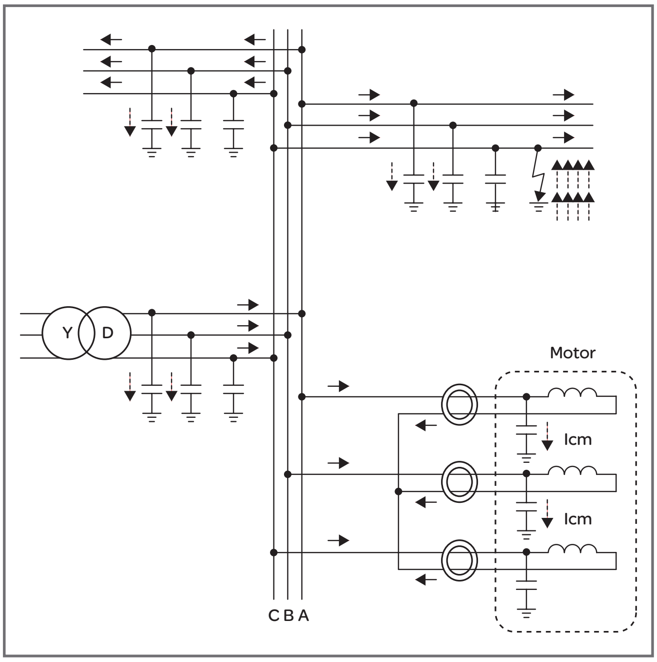

Figure C9.8:
Capacity current distribution under external single phase earth fault

5. Short circuit protection

So if the sum of the capacitive currents of the overall system is larger than the current setting, the self balance winding differential protection can detect the internal single phase earth fault.

5.2.2 Summary

Compared with the conventional differential protection, the self balance winding differential protection does not rely on the consistency of CT characteristics and its reliability is much higher.

The HV motor is connected within the distribution power system. The distribution power system is usually insulated system or high impedance earthing system. So the single phase earth fault current is lower and normally cannot trigger the conventional differential protection. However due to the lower current setting, the self balance differential protection can be sensitive to the single phase earth fault of the HV motor stator.

It should be noted that the protection zone of a self balance differential protection does not normally include the cable between the machine output terminals and controlling switchgear. An additional relay is needed to protect this cable.

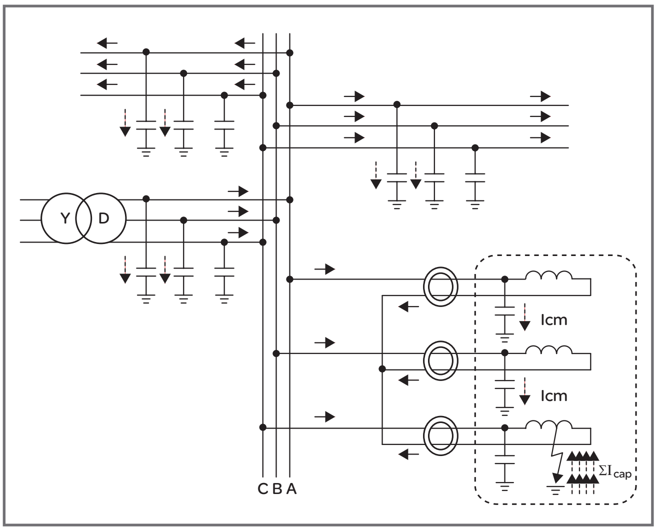

Figure C9.9:
Capacity current distribution under internal single phase earth fault

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.

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 C9.10 can be used.

A lower limit is imposed on the setting by possible load unbalance and/or (for HV systems) system capacitive currents.

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 CTs.

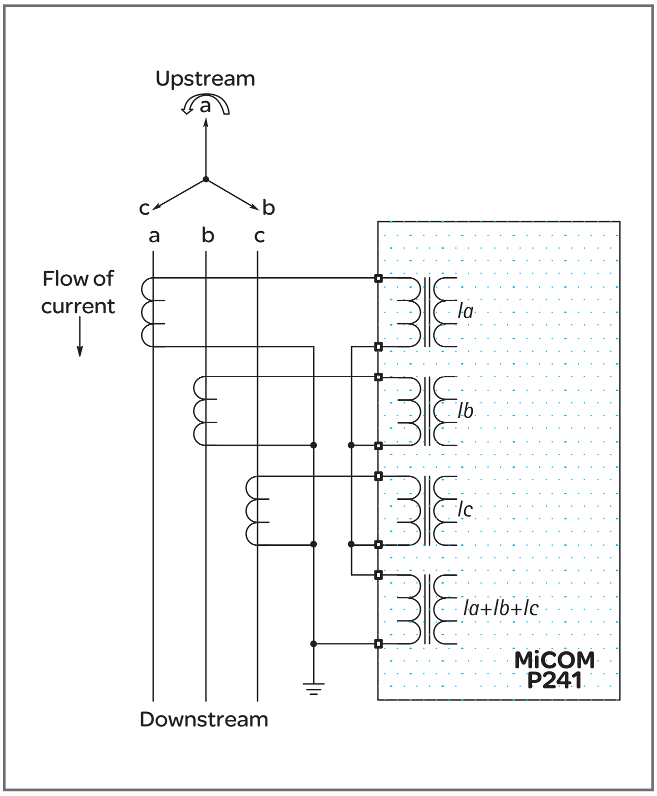

Figure C9.10:
Residual CT connection for earth fault protection

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6. Earth fault protection

It is common to use a stabilising resistor in series with the relay, with the value being calculated using the formula:

$$R_{stab} = \frac{I_{st}}{I_O}\left(R_{ct} + kR_l + R_r\right) \quad \text{...Equation C9.2}$$

where:

I_{st} = starting current referred to CT secondary

I_o = 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)

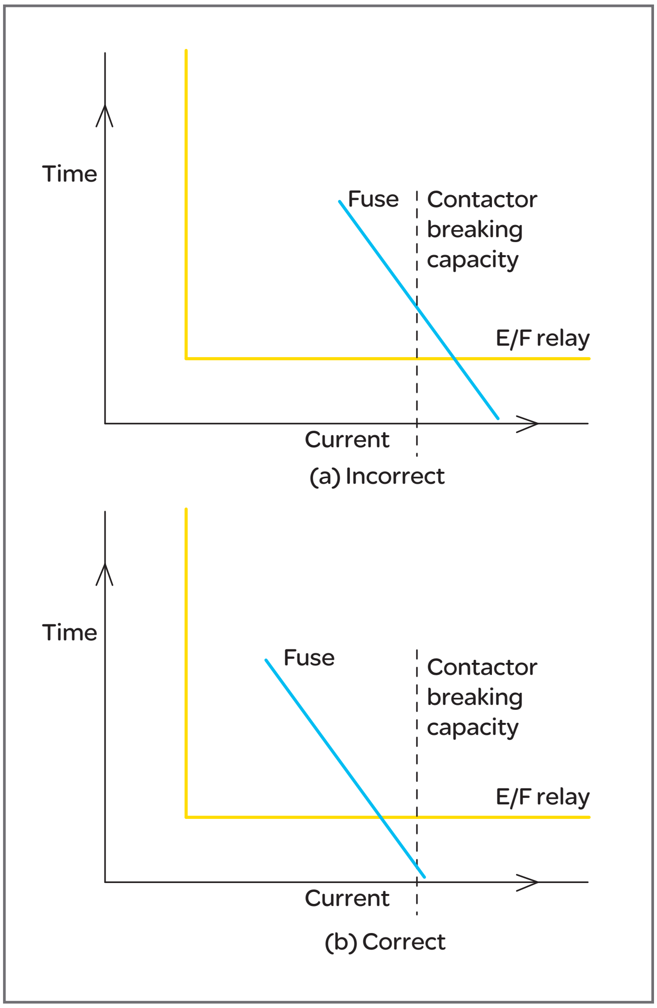

Figure C9.11:
Grading of relay with fused contactor

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 C9.11(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 C9.11(b) illustrates correct grading. To achieve this, it may require the use of an intentional definite time delay in the relay.

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:

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 CTs, the minimum sensitivity possible is about 10% of CT rated primary current, due to the possibility of CT saturation during starting.

For better sensitivity with lower current setting, it is necessary to use a core-balance CT. The primary current of the core-balance CT is no longer related to the normal line current. For a core-balance CT, the relay may be set non-directional with a current sensitivity of less than 30% of the minimum earth fault level but greater than three times the steady state charging current of the motor feeder. The setting should not be greater than about 30% of the minimum earth fault current expected.

If the above setting guidelines for applying a non-directional relay cannot be achieved due to the current magnitudes, then a sensitive directional earth fault element will be required. This eliminates the need to set the relay in excess of the maximum capacitive charging current for the protected feeder.

6. Earth fault protection

The required time delay setting shall ensure that the contactor does not attempt to interrupt fault current in excess of its breaking capacity when the motor is supplied by a fused contactor.

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 capacitive 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° (see Chapter [C1: Overcurrent Protection for Phase and Earth Faults, Section 17 and 18]) for details.

6.3 Insulated earth system

See Chapter [C1: Overcurrent Protection for Phase and Earth Faults, Section 18] for details.

6.4 Petersen coil earthed system

See Chapter [C1: Overcurrent Protection for Phase and Earth Faults, Section 19] for details.

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 C9.12:

- Motor positive sequence impedance at slip s

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

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

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

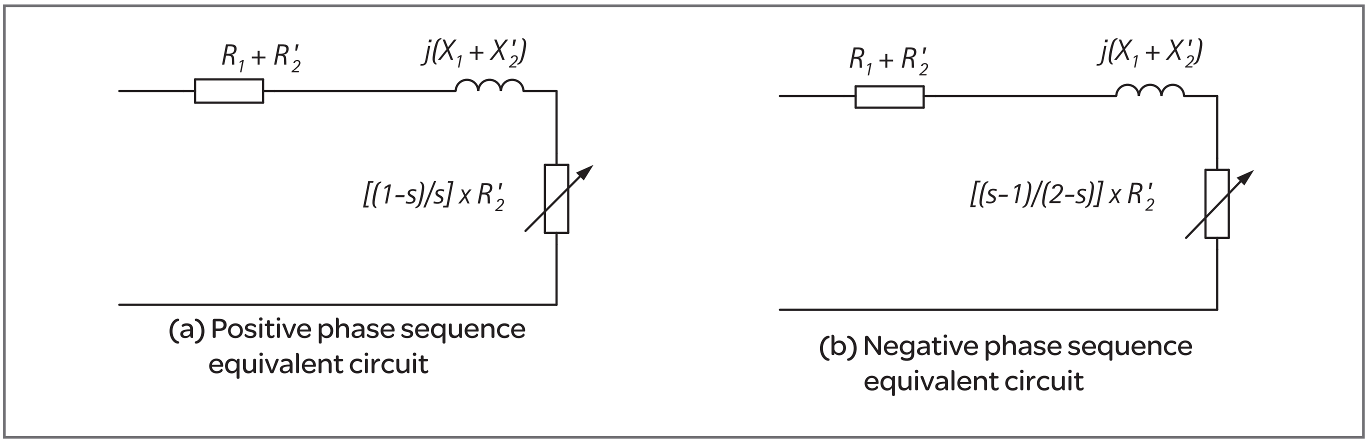

Figure C9.12:
Induction motor equivalent circuit

7. Negative phase sequence protection

and slip s is close to zero 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:

R_1 is the stator resistance

X_1 is the stator leakage reactance

R'_2 is the rotor equivalent resistance referred to stator

X'_2 is the rotor equivalent leakage reactance referred to stator

suffix p indicates positive sequence quantities

and

suffix n indicates negative sequence quantities

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 6xFLC.

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.

Normally 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. This element should be set in excess of the anticipated negative phase sequence current resulting from asymmetric CT saturation during starting, but less than the negative phase sequence current resulting from loss of one phase during starting. 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.

8. Wound rotor induction motor protection

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.

9. RTD temperature detection

RTDs 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 RTDs, thus providing overtemperature protection for the transformer without the use of a separate relay.

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 4 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 9, can provide suitable protection, allowing investigation into the cause of the bearing running hot prior to complete failure.

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.

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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 or a simple undercurrent relay when there is not voltage input, 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.

13. Anti-backspin function

A motor may be driving a very high inertia load. Once the CB or contactor supplying power to the motor is switched off, the rotor may continue to turn for a considerable length of time as it decelerates. The motor has now become a generator and applying supply voltage out of phase may result in catastrophic failure. In some other applications for example when a motor is on a down-hole pump, after the motor stops, the liquid may fall back down the pipe and spin the rotor backwards. It would be very undesirable to start the motor at this time. In these circumstances the anti-backspin function is used to detect when the rotor has completely stopped, in order to allow re-starting of the motor.

This function uses an undervoltage if the phase-phase or single phase remanent voltage of the motor is connected to the relay. The voltage threshold setting for the anti-backspin protection should be set at some low value to indicate that the motor is stopped. If the relay can not get the remanent voltage, this function uses a simple time delay to indicate the motor is stopped after the CB or contactor is open.

14. 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.

14.1 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.

14. Additional protection for synchronous motors

14.2 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.

14.2.1 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.

14.2.2 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 12 for details. A time delay will be required to prevent operation during system transients leading to momentary reverse power flow in the motor.

15. Motor protection examples

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

15.1 Protection of a HV motor

Table C9.2 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 C9.2:
Motor data for example

15.1.1 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, τ_1 and τ_2. τ_2 is used for starting methods other than DOL, otherwise it is set equal to τ_1. τ_1 is set to the heating time constant, hence $\tau_1 = \tau_2$= 25mins. Cooling time constant τ_r is set as a multiple of τ_1. With a cooling time constant of 75mins,

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

15.1.2 Short circuit protection

Following the recommendations of Section 5, with a starting current of 550% of full load current, the short-circuit element is set to 1.25 x 5.5 x 211A = 1450A. In terms of the relay nominal current, the setting value is 1450/250 = 5.8 I_N .

In order to avoid false tripping during start-up, there is a minimum time delay of 100ms for currents in the range 100% to 120% of the setting and a minimum time delay of 40ms for currents above 120% setting. These settings are satisfactory.

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15. Motor protection examples

15.1.3 Earth fault protection

It is assumed that no Core Balance CT is fitted. A typical setting of 30% of motor rated current is used, leading to an earth fault relay setting of 0.3 x 211/250 = 0.25 I_N. A stabilising resistor is required, calculated in accordance with Equation C9.2 to prevent maloperation due to CT spill current during starting as the CTs 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.

15.1.4 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 x 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.

15.1.5 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 15.1.1-5 are shown in Figure C9.13.

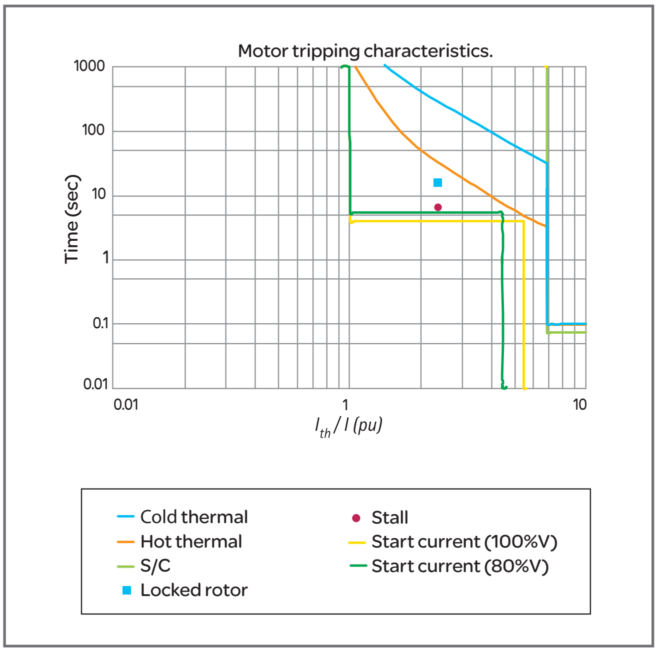

Figure C9.13:
Protection characteristics for motor protection example

15.1.6 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 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 C9.14. 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.

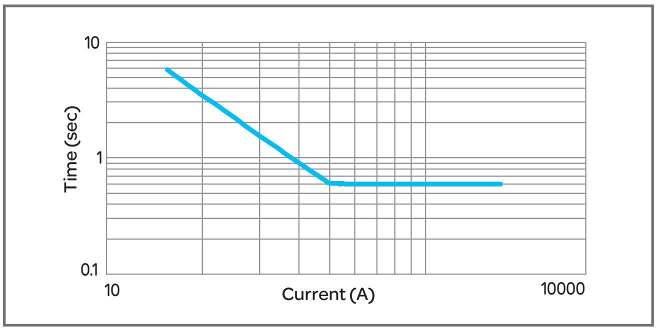

Figure C9.14:
Motor protection example negative sequence protection characteristic

15.1.7 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.

15.2 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 C9.3(a) gives details of an LV motor and associated fused contactor. A MiCOM P211 motor protection relay is used to provide the protection.

15.2.1 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 inthe

15. Motor protection examples

(a) LV motor example data

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

(b) Relay settings

Parameter	Symbol	Value	Unit
Overcurrent		Disabled	-
Overload setting	I_b	4.4	A
Overload time delay	$I>t$	15	s
Unbalance	I_2	20	%
Unbalance time delay	$I_2>t$	25	s
Loss of phase time delay	$<I_p$	5	s

Table C9.3:
LV Motor protection setting example

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.

15.2.2 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.

15.2.3 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 = motor rated primary current

I_p = CT primary current

Hence,

$$I_b = 5 \times 132/150 = 4.4A$$

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 C9.15.

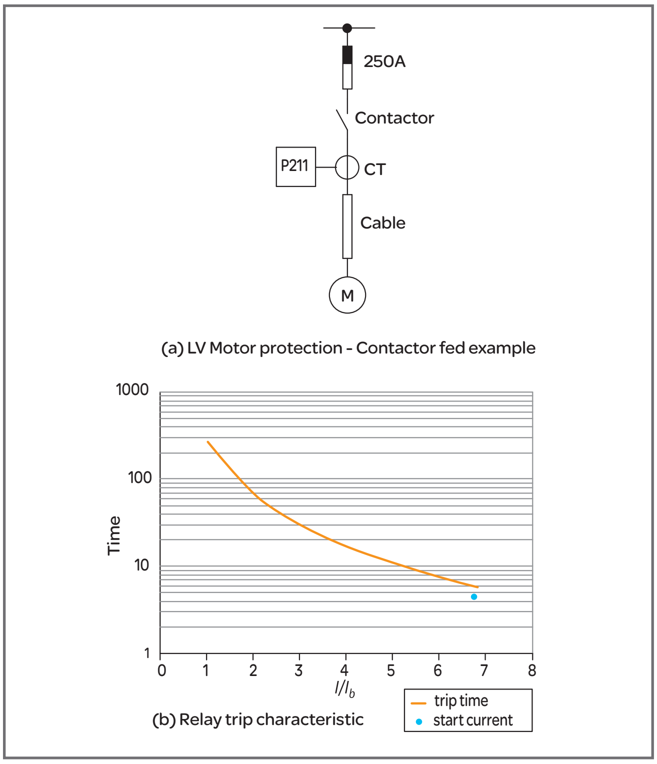

Figure C9.15:
Motor protection example - Contactor-fed motor

15.2.4 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 7). As the relay is fitted only with a definite time relay element, a setting of 20% (from Section 7) is appropriate, with a time delay of 25s to allow for short high-level negative sequence transients arising from other causes.

15.2.5 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 C9.3(b).