17

Motor protection relays

17.1 Introduction

Electric motors are the workhorses of industry and are extensively used to convert electrical energy into rotational mechanical energy. Squirrel cage induction motors, particularly the TEFC type (Totally enclosed, fan cooled), have become extremely popular mainly because of their simple, rugged construction and good starting and running torque characteristics. For example, in a small country such as South Africa, about 100 thousand of this type of motor above 1 kW are sold annually, mainly for new applications but also as replacements for worked out or 'burnt out' motors. The TEFC design improves the mechanical life of the motor because dust and moisture are excluded from the bearings and windings. This type of motor has proved to be extremely reliable with an expected lifetime of up to 40 years when used in the correct application.

The causes of motor damage given in Figure 17.1 are taken from statistics gathered within the ABB Group. They are shown in Figure 17.2, that 81% of these failures could have been avoided by using an accurate and effective relay.

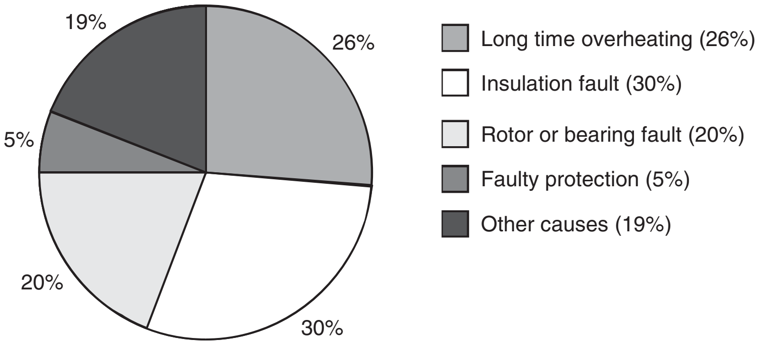


Figure 17.1
Main causes for motor damage in industrial drives

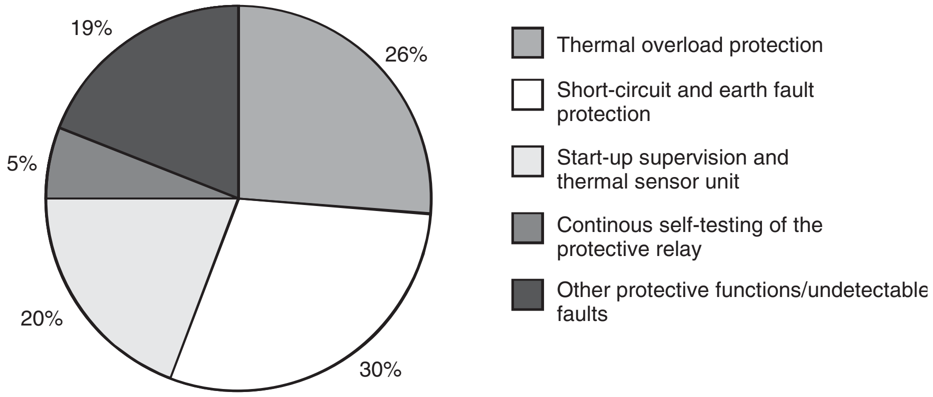


Figure 17.2
Protective functions needed to detect the motor drive faults

The life of an electric motor is determined by the shorter of the following two factors:

1. *Mechanical life*: This is the life of the mechanical parts such as bearings, shaft, fan and the frame and depends on the environment (dust, moisture, chemicals, etc.), vibration and lubrication. The mechanical life can be extended by means of regular inspection and maintenance.
2. *Electrical life*: This is the life of the electrical parts such as the stator winding and insulation, rotor winding and the cable terminations in the motor connection box. Assuming that the cable terminations are properly done and regularly checked, the electrical life may be extended by ensuring that the windings and insulation are not subjected to excessive temperatures which are usually the consequence of overloading or single phasing (loss of one-phase). The purpose of good motor protection is to continuously monitor the current flowing into the motor to detect overloading or fault conditions and to automatically disconnect the motor when an abnormal situation arises. This protection, when correctly applied, extends the useful life of the motor by preventing insulation damage through overheating.

Most people in the industry can easily understand the relatively simple mechanical aspects of an electric motor but few fully appreciate the electrical limitations and relationship of overloading to the useful life of the motor. Essentially, mechanical overloading causes excessively high currents to flow in the winding (since current in the motor is proportional to the load torque) and this results in overheating of the stator and motor windings.

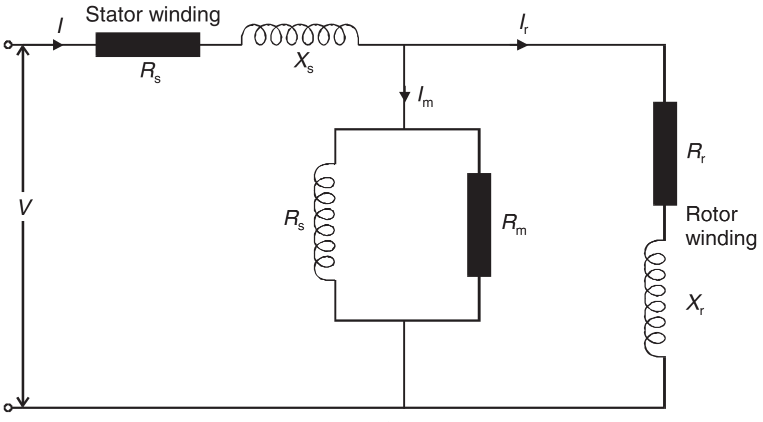
These high temperatures result in the deterioration of the insulation materials through hardening and cracking, eventually leading to electrical breakdown or faults. In many cases, the motor can be repaired by rewinding the stator but this is expensive with a longer downtime. The larger the motor, the higher the cost.

There are several types of insulation materials commonly used on motors. In the IEC specifications for motors, the insulation materials are classified by the temperature rise above maximum ambient temperature, that the materials can continuously withstand without permanent damage. For example, specified temperature rises for commonly used insulation classes are:

Class B:	80 °C above maximum ambient of 40 °C (i.e. maximum continuous temperature of 120 °C)
Class F:	100 °C above maximum ambient of 40 °C (i.e. maximum continuous temperature of 140 °C)

In a squirrel cage induction motor, the current flowing into the stator winding is directly proportional to the mechanical load torque. The motor manufacturer designs the motor to operate within specified limits. The motor is rated in terms of kilowatts (kW) at a rated supply voltage (V) and current (I). This means that a machine can drive a mechanical load continuously up to rated torque at rated speed. Under these conditions, supply current is within the specified current and the internal heating will be within the capabilities of the specified insulation class. At full load with class B insulation, the winding temperature will stabilize at below 120 °C.

The main cause of heating in the motor windings is a function of the square of the current flowing in the stator and rotor windings. This is shown on the motor equivalent circuit of Figure 17.3 where the losses are $I^2 (R_s + R_r)$. These are often referred to as the copper losses. The stator windings have only a small mass and heat up rapidly because of the current flowing. The heat insulation and the cooling time constant is consequently quite long. Other losses also generate heat. These are referred to as the iron losses but are relatively small and are quickly dissipated into the body of the motor.



Equivalent circuit of a squirrel cage motor

I_m = very small value, so $I = I_r$

Copper losses = $I^2(R_s + R_r)$

R_s = stator resistance

R_r = rotor resistance

X_c = magnetizing inductance

R_m = magnetizing resistance

Figure 17.3
Equivalent circuit of a squirrel cage motor

17.2 Early motor protection relays

Some of the early designs of motor protection relays have a single function whose purpose was to protect the motor against overloading by ensuring that it never draws in excess of the rated current. This was done by continuously monitoring the electrical current drawn by the motor and arranging for the motor to be disconnected when the current exceeded the rated current and remains so for a certain period of time. The higher the overload current, the shorter the permissible time before disconnection. This time delay was achieved in various ways. An example is the ‘solder pot’ relay, which relied on the time taken for solder in the measuring circuit to melt when the load current was passed through it. The bi-metal type relays disconnect the motor when the load current passing through a resistor heated in a bi-metallic strip sufficiently to bend it beyond a pre-set limit. This released the trip mechanism. In recent years, electronic relays utilize an analog replica circuit, comprising a combination of resistors and capacitors, to simulate the electrical characteristics of the stator and rotor. The main principle linking all these methods is the design of a replica system to simulate as closely as possible the electrical characteristics of the motor.

In the past, it has been a common practice to detect over temperature from temperature-dependent elements built into the winding of the motor.

However, this form of temperature measurement is in most cases unsatisfactory, as it is not taken directly from the current conductor. Instead, it is taken through the insulation which gives rise to considerable sluggishness. Due to insulation considerations, insertion of thermocouples in high-voltage motors can cause problems. Furthermore, after a fault (e.g. a break in the measuring lead inside the machine) high repair costs are encountered. Another problem is that no one can accurately predict, during the design, how many and where the ‘hot spots’ will be.

Consequently, protection is preferably based on monitoring the phase currents instead. Because the temperature is determined by the copper and iron losses, it must be possible to derive it indirectly by evaluating the currents in the motor supply leads.

The performance of a motor protection relay depends on how closely and accurately the protection simulates the motor characteristics. The ideal simulation occurs when the heating and cooling time constants of the motor windings are matched by the relay under all operating conditions. In some of the early devices, the protection could underestimate the heating time of the windings from cold and could trip before a motor/load combination with a long run-up time had reached running speed. On the other hand, during several sequential starts and stops, the device could underestimate the cooling time of the windings, allowing the motor windings to overheat. This situation can very easily arise with the bi-metallic thermal overload relays commonly used on motor starters even today. Under certain conditions, bi-metallic thermal overload relays do not provide full protection because the device does not have exactly the same thermal heating and cooling characteristics as the motor, which it is protecting. The heating and cooling time constants of a bi-metallic relay are much the same but in actual installations, it should be borne in mind that a stopped motor has a longer cooling time constant than that for a running motor. When a motor has stopped, the fan no longer provides a forced draft and cooling takes longer than when the motor is running on no load. A simple bi-metallic device is a compromise and is calibrated for normal running conditions. As soon as an abnormal situation arises, difficulties can be expected to arise.

To illustrate the point, take the case of a motor that has been running at full load for a period of time when the rotor is suddenly stalled. Figure 17.4 shows typical temperature curves of the winding temperature (solid line) compared to the heating and cooling curve of the protective device (dotted line). Starting at a normal continuous running temperature of 120 °C, the current increases for the locked rotor condition and temperature rises to 140 °C when the thermal device trips the motor after some seconds. After about 10 min, the bi-metal will have cooled to ambient, but the windings will only have reading 100 °C. With the bi-metal reset, it is then possible to attempt a restart of the motor. With the rotor still locked, high starting currents cause the temperature to quickly rise to 165 °C before the bi-metal again trips the motor.

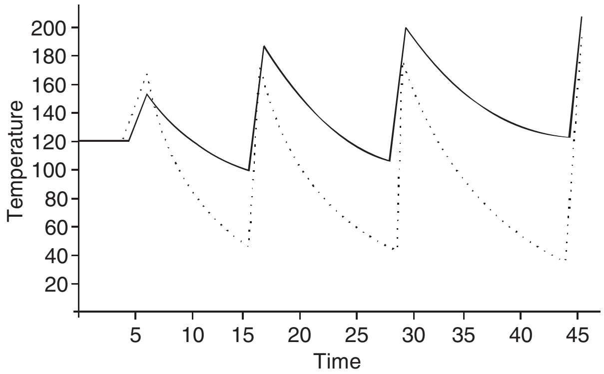


Figure 17.4
Temperature rise vs time for a motor

Consider repeating similar sequence of events as described above, where the different cooling times of the motor and bi-metal strip allow the bi-metal to reset before the windings have cooled sufficiently, and if the motor is again restarted after another 10 min, the winding temperature is likely to exceed 180 °C, the critical temperature for class B insulation materials. This illustrates the importance of an accurate simulation by the protection device in both conditions where the motor is running and when the motor is stopped.

17.3 Steady-state temperature rise

In the interest of maximum efficiency, electrical machines should be loaded as close as possible to their permitted operating temperature limit; however, excessive thermal stressing of any appreciable duration must be avoided if the life of the insulation is not to be shortened.

Under steady-state conditions, the temperature of a motor will rise exponentially, due to dissipation of the heat to the environment or cooling medium, towards its respective operative temperature. Since a motor is not a homogeneous mass, heat is dissipated in several stages. Temperature rise and fall takes place according to a series of partial time constants. Refer to Figure 17.5.

In spite of this, it is sufficient for a thermal overload relay intended for protection under steady-state conditions to be set to the mean time constant of the motor. This means that proper account is taken only of the copper losses. Measurement of the voltage would be necessary in order to include the iron losses, but is not generally possible since the voltage transformers are usually located on the busbar and not adjacent to each motor. Most modern thermal overload relays only measure current, filtering out the highest of the three-phase current. The critical cases of starting, stalling and failure of a phase are taken care by other protective functions.

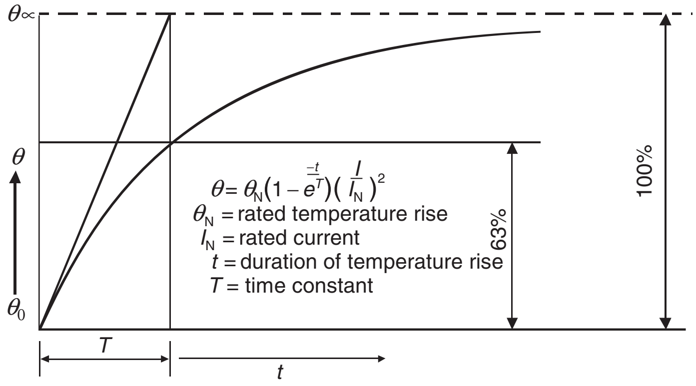


Figure 17.5
Temperature rise vs time (illustrating time constant)

17.4 Thermal time constant

The time constant T (tau) is defined (IEC 255-8) as the time in minutes required for the temperature of a body to change from an initial temperature θ_0° to 63% of the difference between θ_0° and the new steady-state temperature θ_∞.

Unfortunately, the thermal time constant T of the motor is frequently not known. Table 17.1 gives typical values in relation to motor ratings and mechanical design. The cooling time constants during operation are approximately equal to those for temperature rises, while at standstill they are 4–6 times the values given in the table.

Type \ A[mm]	355	400	450	500	560	630	710	800	900	1000	1120	1250
O	20	25	28	30	35	40	50	60	65	70		
R				45	50	55	60	70	80	90	100	110
U	30	35	40	45	50							

A = Shaft height (mm)
O = Open type (IP23)
R = Closed type with air/air heat-exchanger (IP54)
U = Fully clad with cooling finds (IP54)

Table 17.1
Mean thermal time constants of asynchronous motors from Brown Boveri in relation to motor rating and type

17.5 Motor current during start and stall conditions

As the magnitude and duration of motor starting currents and the magnitude and permissible duration of motor stalling currents are major factors to be considered in the application of overload protection, these will be discussed. It is commonly assumed that the machines started direct-on-line the magnitude of the starting current decreases linearly as the speed of the machine increases. This is not true. For normal designs, the starting current remains approximately constant at the initial value for 80–90% of the total starting time. Refer to Figure 17.6. When determining the current and time settings of the overload protection, it can be assumed that the motor starting current remains constant and equal to the standstill value for the whole of the starting time.

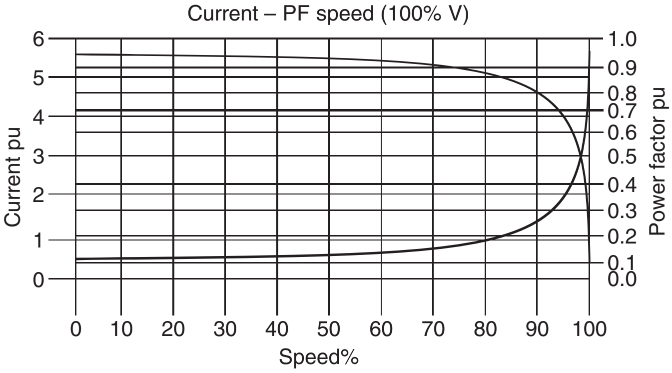


Figure 17.6
Motor current during start conditions

17.6 Stalling of motors

Refer to Figures 17.7 and 17.8. Should a motor stall when running or be unable to start (run) because of excessive load, it will draw a current from the supply equivalent to its locked rotor current. It is obviously necessary to avoid damage by disconnecting the machine as quickly as possible if this condition arises. It is not possible to distinguish this condition from a healthy starting condition on current magnitude.

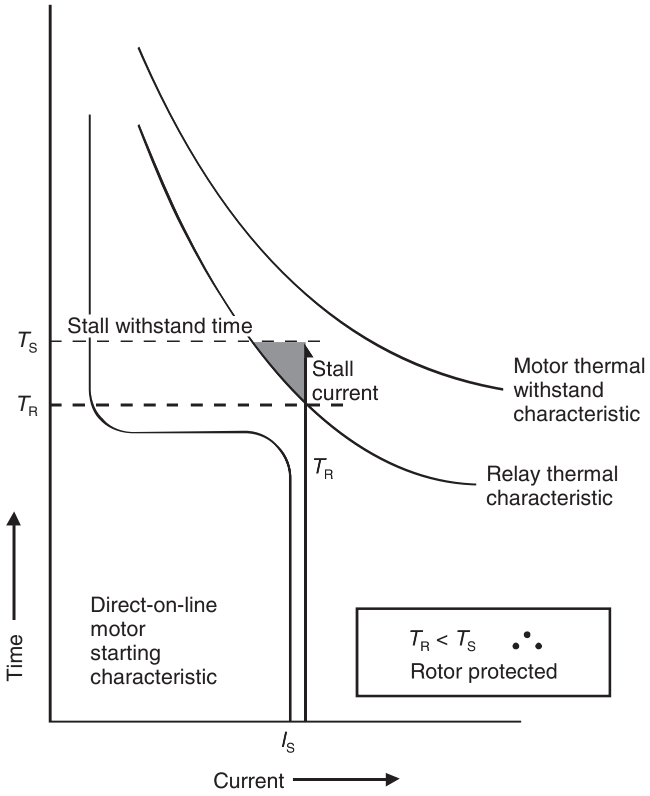


Figure 17.7
Relay operation time less than stall withstand time: relay gives stall protection

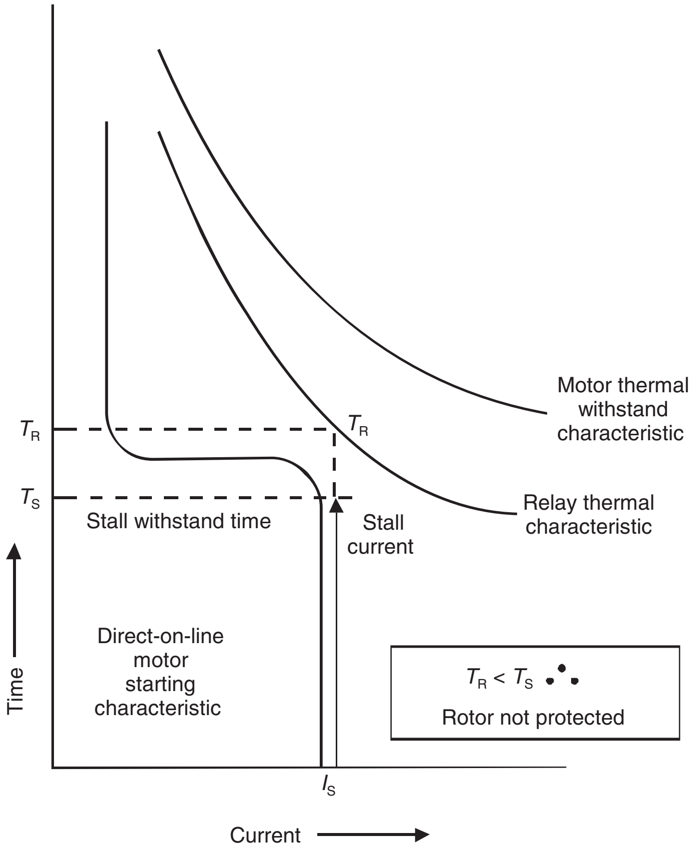


Figure 17.8
Relay operation time greater than stall with stand time: relay does not give stall protection

The majority of loads are such that the starting time of normal induction motors is about or less than 10 s, while the allowable stall time to avoid damage to the motor insulation is in excess of 15 s.

If a double cage drive is to be protected, it might be that the motor cannot be allowed to be in a stall condition even for its normal start-up time. In this case, a speed switch on the motor shaft can be used to give information about whether the motor is beginning to run-up or not. This information can be fed to suitable relays, which can accelerate their operating time. Refer to Figures 17.9(a), (b).

Whether or not additional features are required for the stalling protection, depends mainly on the ratio of the normal starting time to the allowable stall time and the accuracy with which the relay can be set to match the stalling time/current curve and still allow a normal start.

17.7 Unbalanced supply voltages

The voltage supplied to a three-phase motor can be unbalanced for a variety of reasons; single-phase loads, blown fuses in pf capacitors, etc. In addition, the accidental opening of one-phase lead in the supply to the motor can leave the motor running, supplied by two phases only.

It might seem that the degree of voltage unbalance met within a normal installation (except when one-phase is open circuited) would not affect the motor to any great extent, but this is not so. It should be remembered that it is not the unbalanced voltage which is important, but the relatively much larger negative sequence component of the unbalance current, resulting from the unbalanced voltage.

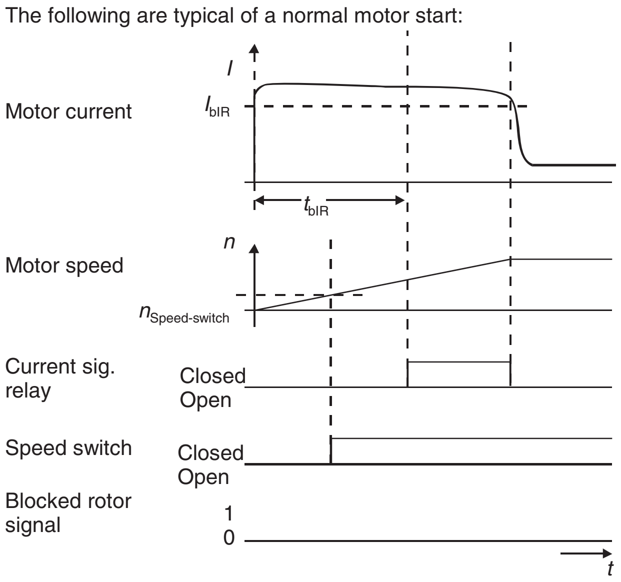


Figure 17.9(a)
Typical motor start

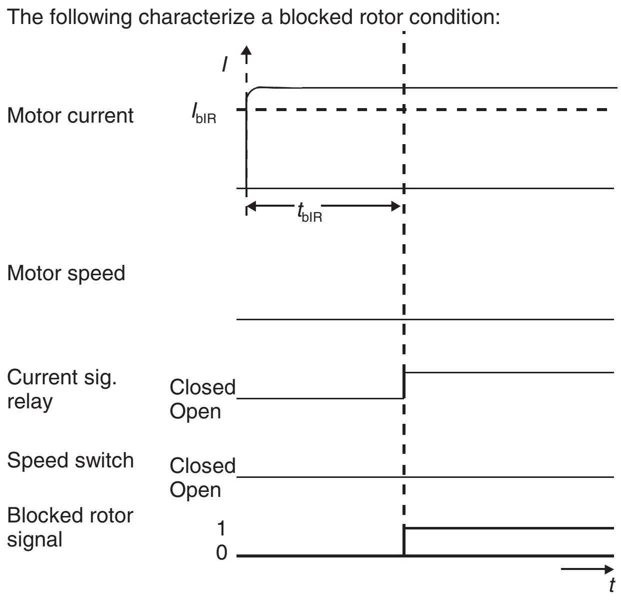


Figure 17.9(b)
Blocked rotor condition

The method of symmetrical components consists of reducing any unbalanced three-phase systems of vectors into three balanced systems: the positive, negative and zero sequence components (see Figure 17.10). The positive sequence components consist of three vectors equal in magnitude 120° out of phase, with the same phase sequence or rotation as that of the source of supply. The negative sequence components are three vectors equal in magnitude, displayed by 120° with a phase sequence opposite to the positive sequence. The zero sequence components consist of three vectors equal in magnitude and in a phase.

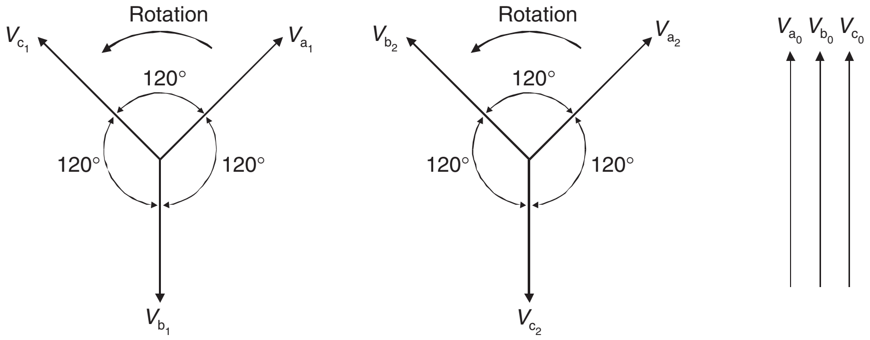


Figure 17.10
The positive, negative and zero components

Loss of one-phase represents the most dangerous case of unbalance. It is therefore essential for motors, which are protected against short circuit by fuses (limited breaking capacitor of the breaker) to be equipped with fast-operating loss of phase protection.

17.8 Determination of sequence currents

In the general case of unbalanced three-phase voltages, there is no fixed relationship between the positive and negative sequence currents; the actual value of the negative sequence current depends on the degree of unbalanced supply voltage, and on the ratio of the negative to the positive sequence impedance of the machine. The ratio can be determined from the general equivalent circuit of the induction motor.

Since in an induction motor the value of the resistance is normally small compared with the reactance, the negative sequence impedance at normal running speeds can be approximated to the positive impedance at standstill. The ratio of the positive sequence impedance to the negative sequence at normal running speeds can thus be approximated to the ratio of the starting current which will therefore be approximately equal to the product of the negative sequence voltage and the ratio of the starting current to the full-load running current.

For instance, in a motor, which has a starting current equal to 6 times rated current, a 5% negative sequence component in the supply voltage would result in approximately a 30% negative sequence component of current.

17.9 Derating due to unbalanced currents

The negative sequence component of the current does not contribute to providing the driving torque of the motor; in fact, it produces a small negative torque. The magnitude of the torque due to the negative sequence current is, however, usually less than 0.5% of the full-load-rated torque for a voltage unbalance in the order of 10% and can therefore be neglected. Hence, presence of negative sequence currents does not appreciably affect the starting characteristics.

The main effect of the negative sequence current is to increase the motor losses, mainly copper loss, thus reducing the available output of the machine if overheating of the machine windings is to be avoided. The reduction in output for the machines having ratios of starting to running current of 4, 6 and 8 respectively is shown in Figure 17.11 for various ratios of negative to positive sequence voltage.

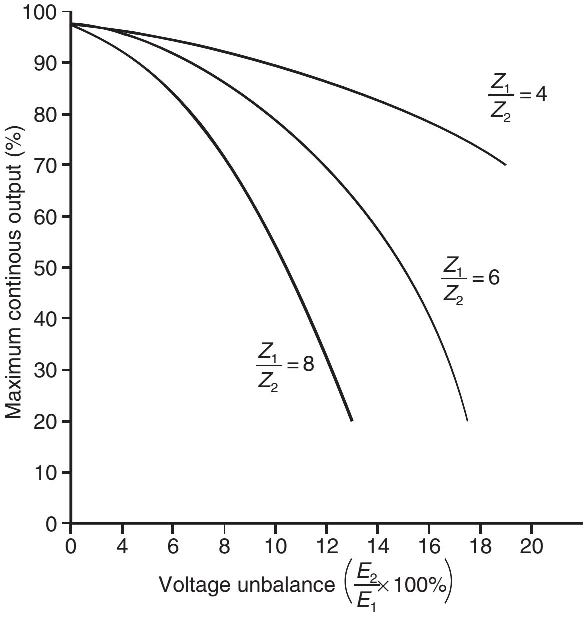


Figure 17.11
Maximum continuous output vs voltage unbalance

17.10 Electrical faults in stator windings earth faults phase–phase faults

17.10.1 Earth faults

Faults, which occur within the motor windings are mainly earth faults caused by breakdown in the winding insulation. This type of fault can be very easily detected by means of an instantaneous relay, usually with a setting of approximately 20% of the motor full-load current, connected in the residual circuit of three current transformers.

Care must be taken to ensure that the relay does not operate from spill current due to the saturation of one or more current transformers during the initial peak of the starting current; this can be as high as 2.5 times the steady-state rms value, and may cause operation, given the fast-operating speed of the normal relay. To achieve stability under these conditions, it is usual to increase the minimum operating voltage of the relay by inserting a stabilizing resistor in series with it. Refer Figure 17.12.

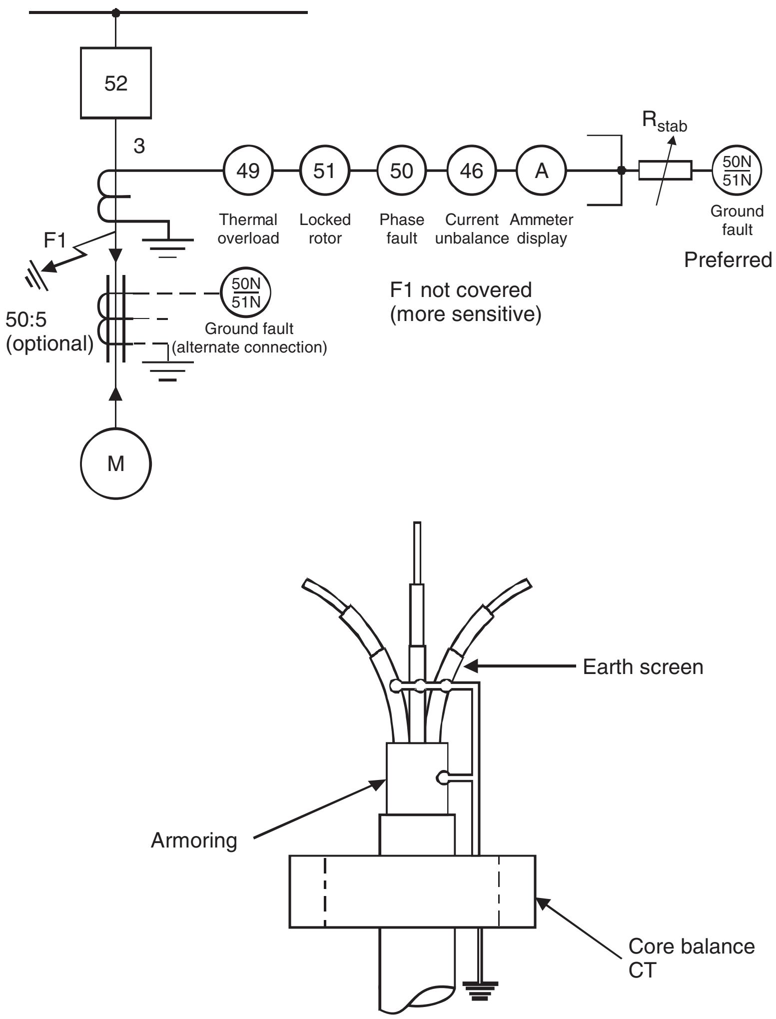


Figure 17.12
Earth fault protection

17.10.2 Phase–phase faults

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 described above.

Differential protection is sometimes provided on large (2 MW) and important motors to protect against phase–phase faults, but if the motor is connected to an earthed system there does not seem to be any great benefit to be gained if a fast-operating and sensitive earth fault is already provided.

17.10.3 Terminal faults

High-set instantaneous overcurrent relays are often provided to protect against phase faults occurring at the motor terminals, such as terminal flashovers. Care must be taken when setting these units to ensure that they do not operate on the initial peak of the motor starting current, which can be 2.5 times the steady-state rms value.

The asymmetry in the starting current rapidly decreases, and has generally fallen to its steady-state value after one cycle. A typical motor starting current is shown in Figure 17.13.

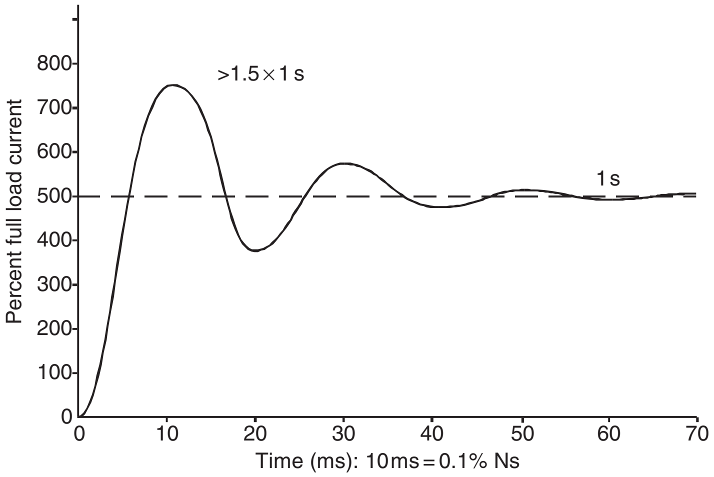


Figure 17.13
Transient overcurrent during first few cycles when starting a motor

17.11 General

The bi-metal thermal overload relay has proved itself an effective and economical solution for small to medium-sized motors up to about 22 kW. On larger, more expensive motors or when maximum motor utilization is required under varying operational conditions more sophisticated flexible and accurate microprocessor protection relays should be considered.

These relays typically include:

- Thermal overload protection, monitoring all three-phases with thermal replicas for direct and frequency convertor-controlled drives
- Short-circuit protection
- Start-up and running stall protection
- Phase unbalanced protection
- Single-phasing protection
- Earth fault protection
- Undercurrent protection
- Digital read-out of set values, actual measured values and memorized values
- Self, supervision system
- Outstanding accuracy
- Optimum philosophy.

The present day concept is use of microprocessor-based numerical relays for both HV and LV motors (say beyond 50 kW), as the relays come with lot of features which allow them to be interchangeable, ensures site settings and give valuable feedback on the load details whether a trip occurs or not.

17.12 Typical protective settings for motors

(a) Long time pick-up

- 1.15 times motor FLA times motor service factor for applications encountering 90% voltage dip on motor starting
- 1.25 times motor FLA times motor service factor for applications encountering 80% voltage dip on motor starting.

(b) Long-time delay

- Greater than motor starting time at 100% voltage and the minimum system voltage
- Less than locked rotor damage time at 100% voltage and the minimum system voltage
- On high-inertia drives, it is common for the start time to be greater than the locked rotor withstand time. Under these circumstances, set the time to permit the motor to start. Supplemental protection should be added for locked rotor protection. One example of this is a speed switch set at 25% of rated speed tripping through a timer to trip if the desired speed has not been reached in a pre-determined time.

(c) Instantaneous pick-up

- Not less than 1.7 times motor LRA for medium-voltage motors
- Not less than 2.0 times motor LRA for low-voltage motors.

(d) Ground-fault protection

- Minimum pick-up and minimum time delay for static trip units
- Core-balance CT and 50 relays set at minimum for medium-voltage, low-resistance grounded systems
- Residually connected CT, and 50/51 for medium voltage, solidly grounded systems. Minimum tap and time dial equals 1 for 51 relay
- Minimum tap (not less than 5 A) for 50 relay.