Optimum Motor Protection with SIPROTEC Protection Relays

Power Transmission and Distribution

SIEMENS

Optimum Motor Protection with SIPROTEC Protection Relays

Contents

Introduction to the Principles of Asynchronous and Synchronous Motors

This chapter is an introduction to three-phase motors. On the basis of fundamental physical relationships and their structure, it is particularly the characteristic operating modes of motors which are discussed. Essential mathematical relationships, as are needed when deriving characteristic quantities of motors or for protection settings, are also presented.

■ 1. Basic principle of the three-phase machine

Electric machines convert electrical energy into mechanical energy. The energy conversion process is based on the interaction of magnetic fields and windings. In its electrically active part, a rotary electric machine consists of a stator with a rotating field winding and the rotor. The rotor is connected to the shaft, through which mechanical energy is dissipated (in the case of the motor). A rotating magnetic field (rotating field) is the fundamental prerequisite for the operation of three-phase machines. This is generated by connecting a three-phase winding to a symmetrical three-phase system. For a sinusoidal profile of the rotating field, the three phases must be placed at a 120° offset and there must be a 120° offset between the individual phase currents. The rotating field's rotation speed is called the synchronous speed n_{syn} and is defined by the machine's number of poles and the frequency of the supplying power system. The following applies:

$n_{syn} \quad = f \cdot 60/p \;\; [\text{rpm}]$

where: p = number of pole pairs

Operating principle of the asynchronous machine

A voltage is induced in the rotor's conductors if there is a difference between the rotation speed of the rotating field and the rotor (induction law). If the conductors are part of a closed winding, the induced voltage produces a flow of current. This leads to tangential forces according to the force effect of a current-carrying conductor in the magnetic field. The sum of all tangential forces generates a resulting torque over the rotor's radius acting as a fulcrum.

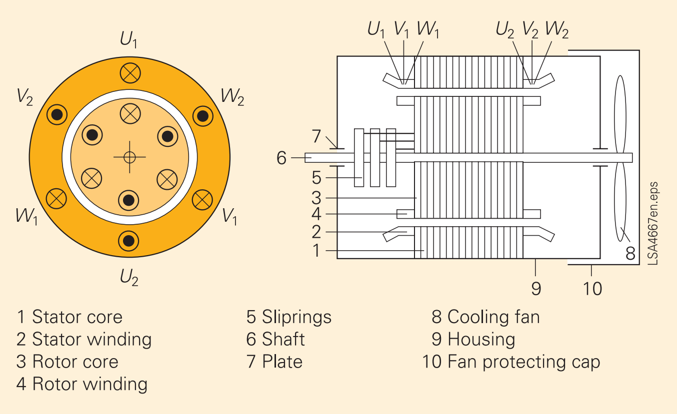

Fig. 1 Principal components of the three-phase asynchronous machine (U, V, W: conductor terminals U_{L1}, U_{L2} and U_{L3})

According to Lenz's Rule, the force effect between currents and the rotating field is oriented such that it counteracts the cause of induction. If the rotating field of the machine still at standstill runs beyond the rotor, it begins to turn in the rotating field's direction to reduce the relative speed between the rotating field and the rotor. The frequency (speed) of the rotor can never reach the rotating frequency of the stator, because a voltage is then no longer induced in the rotor and so the force effect becomes zero. The deviation between the frequency of the rotating field and the frequency of the rotor is referred to as slip s. Slip sets in so that a rotor current that is still just adequate for the motor's load arises.

$$s = \frac{\omega_{rf} - \omega_r}{\omega_{rf}} = \frac{f_{rf} - f_r}{f_{rf}} = \frac{n_{syn} - n_r}{n_{nsyn}} \qquad (1)$$

ω_{rf}	angular frequency of the stator's rotating field ($\omega_{rf} = \omega_S$)
ω_r	angular frequency of the rotor
f	frequency
n	speed

The resulting speed of the motor (rotor) results from the number of pole pairs p (p =1 signifies 2 poles, as shown in Fig. 1) and the slip.

$$n_r = n_{syn}\,(1 - s) \qquad (2)$$

It was the imbalance between the frequencies of the rotating field and the rotor that led to the name **asynchronous machine**. Due to the voltage induced, the term induction machine is frequently used, too.

Structure of an asynchronous machine

Fig. 1 shows, in a longitudinal section and a cross-section, the principal components of a three-phase asynchronous machine with a slipring rotor. The number of pole pairs is p = 1.

Stator

The stator core secured on the housing accommodates the isolated three-phase stator winding in mostly half-closed slots. The stator core consists of mutually isolated electrical steel sheets. Lamination of the stator and rotor is necessary to minimize the eddy current losses arising due to the alternating magnetic fields.

The three phases of the stator winding are connected in either star or delta form. Therefore it is possible to operate the machines with different rated voltages. Thus, machines in a star connection operated at 400 V can also be operated at 230 V with unchanged power output by changing over to a delta connection. Star-delta starting is also possible if machines are operated at rated voltage in a delta connection.

Rotor

The three-phase rotor core, which is also isolated, is housed in half or fully closed slots of the rotor core. The ends of the rotor winding phases are connected in a star point. The starts of the windings are routed to sliprings so that the winding can be shorted directly or with the aid of resistors.

Contrary to the slipring rotor, the winding of the squirrel-cage motor consists of simple conductor bars without additional insulation. These conductor bars are distributed concentrically around the shaft on the rotor's circumference and are shorted by rings at the face ends of the rotor core. The resulting winding cage led to the name of squirrel-cage rotor. The starting response of the motor (see also Section 3) can be influenced by special cross-sectional shapes of the rotor bars (see Fig. 2) or by using two cages (double squirrel-cage rotor).

With a view to minimizing the magnetization current as far as possible, the air gap between the stator and rotor cores must be kept very small. As all slot openings along the rotor or stator circumference act like an enlargement of the air gap and lead to distortions of the air gap's field (voltage distortions and additional losses), the slots are generally half-closed, to some extent entirely closed and only designed as open slots in the case of high-voltage machines.

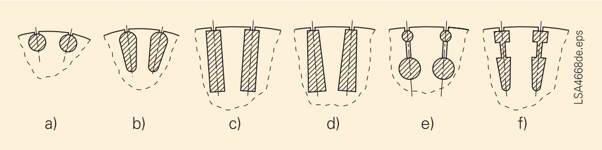

Fig. 2 Bar shapes of a squirrel-cage rotor
a) Round bar rotor
b) Squirrel-cage rotor with parallel-flanked teeth for cast cages
c) Deep-bar rotor with rectangular bars
d) Deep-bar rotor with tapered bars
e) Double squirrel-cage rotor with round bars
f) Double squirrel-cage rotor with parallel-flanked teeth for cast cages

Operating principle of the synchronous machine

In the case of the **synchronous machine**, the rotating field and rotor frequencies are identical and so the slip is equal to zero. Both rotating fields run synchronously. As already explained above, the principle of the induction machine therefore fails. The magnetic field required for energy turnover is generated with the aid of an excitation winding. In the case of electrically excited synchronous machines, an adjustable direct current is needed for the excitation winding. This is supplied with the aid of an excitation system. In the case of brushless excitation, as takes place especially in large synchronous machines, the excitation power is fed by means of an excitation machine fitted on the motor's shaft and with a synchronously rotating three-phase bridge circuit. This directly generates the excitation voltage. As an alternative, the excitation power can also be fed via sliprings.

One positive characteristic of the synchronous machine is the possibility of synchronous compensator operation. A reactive power can be generated in a required form, thus improving a power system's power factor (cos φ).

2. Equivalent circuit diagram of the asynchronous machine and mathematical relationships

Essential characteristic quantities are to be derived with reference to the example of the equivalent circuit diagram. We can find analogies to the transformer, and so the asynchronous motor's equivalent circuit diagram (see Fig. 3) can be derived from that of the transformer. The rotor variables are converted to the variables of the stator via magnetic coupling. Similarly to the transformer, this is done with the square of the number of turns per unit length of the rotor and stator windings (see equation (3)). To simplify matters, the iron losses are ignored.

$$R'_r = \left(\frac{W_S}{W_r}\right)^2 R_r \tag{3}$$

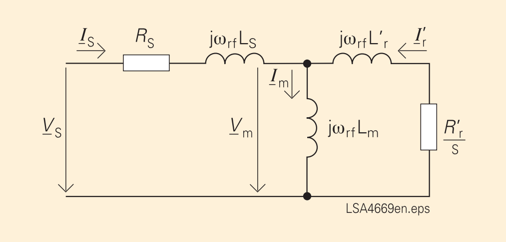

Fig. 3 Equivalent circuit diagram of the asynchronous motor

It becomes clear that the effective rotor resistance is low during starting (s = 1). The high starting current with a low cosφ is the result of this. During normal operation, at s → 0 the effective resistance is high and the cosφ approaches the value 1.

The necessary mathematical relationships are shown below. Equation (4) shows the stator current as the sum of the rotor and magnetizing currents ($\underline{I}_m$). If we neglect the idle current, the stator current is approximately equal to the transformed rotor current.

$$\underline{I}_S = \underline{I}_m - \underline{I}'_r = \frac{\underline{V}_m}{j\omega_{rf}\, L_m} - \frac{\underline{V}_m}{\frac{R'_r}{s} + j\omega_{rf}\, L'_r} \approx \frac{\underline{V}_S}{R_S + \frac{R'_r}{s} + j\left(X_S + X'_r\right)} \tag{4}$$

The power factor results from the real portion of the rotor current in equation (4) and leads to the relationship in equation (5).

$$\cos\varphi_r = \frac{\frac{R'_r}{s}}{\sqrt{\left(\frac{R'_r}{s}\right)^2 + \left(X'_r\right)^2}} \tag{5}$$

A further characteristic quantity is the machine's torque, which can be derived from the power balance. The mechanical power given off P_{mech} is the result of the difference of the electrical effective power P_s supplied minus the losses in the stator $P_{loss\text{-}s}$ and rotor $P_{loss\text{-}r}$ of the machine.

$$P_{mech} = P_s - P_{loss\text{-}s} - P_{loss\text{-}r} \tag{6}$$

The following applies if we neglect the stator losses and introduce the air gap power Pσ:

$$P_{mech} = P_\sigma - P_{loss\text{-}r} \tag{7}$$

The mechanical power can be expressed with the aid of the torque M and the mechanical angular velocity ω_{mech} of the rotor.

$$P_{mech} = M\,\omega_{mech} = M\,\frac{\omega_{rf}}{p}\left(1 - s\right) \tag{8}$$

By analogy, the torque can be calculated from both the air gap power and the rotor's dissipated power using the following equation.

$$M = \frac{P_\sigma}{\omega_{rf}}\,p \quad \text{or} \quad M = \frac{P_{loss\text{-}r}}{\omega_{rf}}\,\frac{p}{s} \tag{9}$$

After neglecting the stator losses, we can calculate the rotating field's power from the stator voltage (phase voltage) and the real portion of the stator current which, for a three-phase machine, results in the following:

$$P_\sigma = 3 \cdot U_S\, Re\left(\underline{I}_S\right)$$

where

$$\mathrm{Re}\left(\underline{I}_S\right) = \frac{U_S \cdot \frac{R'_r}{s}}{\left(R_S + \frac{R'_r}{s}\right)^2 + \left(X_S + X'_r\right)^2} \tag{10}$$

Inserted in equation (9), equation (10) leads to the final relationship for the machine's torque

$$M = \frac{3pU_S^2}{\omega_{rf}} \frac{\frac{R'_r}{s}}{\left(R_S + \frac{R'_r}{s}\right)^2 + \left(X_S + X'_r\right)^2} = \frac{3pU_S^2}{\omega_{rf}} \frac{1}{\frac{R_S^2 + \left(X_S + X'_r\right)^2}{R'_r}\, s + \frac{R'_r}{s} + 2\,R_S} \tag{11}$$

By derivation of the denominator of equation (11), which is set to zero, we can calculate the slip at which the torque reaches the extreme value. This slip is referred to as the pull-out slip s_{pull}. Consequently, the torque developing with this slip is the pull-out torque.

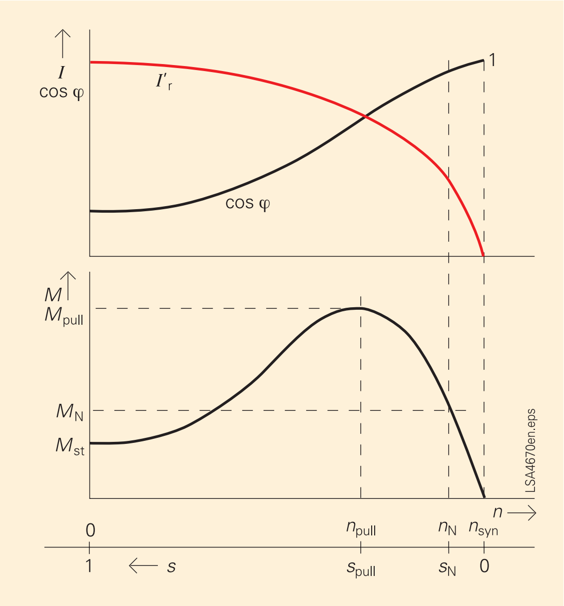

Fig. 4 Operating quantities of the asynchronous motor as a function of the rotor's speed or the slip (M_{st} starting torque, M_{pull} pull-out torque; M_{N} rated torque, n_{pull} pull-out speed, $n_{\text{syn}} = n_{\text{rf}}$ speed of the stator's rotating field, s_{pull} pull-out slip, s_{N} rated slip)

$$s_{\text{pull}} = \frac{R'_{\text{r}}}{\sqrt{R_{\text{S}}^2 + \left(X_{\text{S}} + X'_{\text{r}}\right)^2}} \tag{12}$$

$$M_{\text{pull}} = \frac{3pU_{\text{S}}^2}{2\,\omega_{\text{rf}}} \frac{1}{\sqrt{R_{\text{S}}^2 + \left(X_{\text{S}} + X'_{\text{r}}\right)^2} + R_{\text{S}}} \tag{13}$$

If we relate equations (11) and (13) and if we neglect the ohmic stator resistance, we arrive at the so-called "Kloss relationship". This formula (equation (14)) describes the torque-slip characteristics for the entire slip range ($-\infty < s < +\infty$). The relationship for the pull-out slip is also simplified.

$$\frac{M}{M_{\text{pull}}} = \frac{2}{\dfrac{s}{s_{\text{pull}}} + \dfrac{s_{\text{pull}}}{s}} \quad \text{where } s_{\text{pull}} = \frac{R'_{\text{r}}}{X_{\text{S}} + X'_{\text{r}}} \tag{14}$$

Thus, we have derived essential mathematical relationships for the operating variables of the asynchronous motor. These help when interpreting the curves and data supplied by the manufacturer of the motor. In quality terms, Fig. 4 shows the course of the characteristic quantities. The typical characteristics are also plotted.

Equation (4) shows that the starting current depends on the applied voltage and particularly on the resistance of the rotor. The rotor's equivalent resistance is designed low so as to keep losses in the rotor likewise low. This leads to relatively high starting currents, which can certainly reach values of five to eight times the rated current. As demonstrated in equation (11), the low equivalent resistance of the rotor limits the starting torque.

There are limits to reducing the starting current by decreasing the stator voltage. Equation (11) clearly shows the square dependence of the torque on the applied stator voltage ($M \sim V^2$), which leads to a drastic reduction in the starting torque (half the terminal voltage leads to a quarter of the original torque).

Increasing the rotor resistance by means of starting resistors (slipring rotor motor as shown in Fig. 1) leads to reduction of the starting current. As a result, the cosφ and thus the starting torque increase. During normal operation, the resistors are shorted. The drawback of this solution is the greater effort involved.

From the square voltage dependence of the torque we can also derive that, as demonstrated in equation (13), the pull-out torque is also clearly reduced. Thus, when operating a motor with a reduced voltage, we run the risk of the required mechanical torque exceeding the pull-out torque, resulting in a possibility that the motor will literally stand still.

■ 3. *Startup of asynchronous motors*

From the point of view of the power system, appropriate proof must be provided of reliable starting (from standstill) and restarting (from a particular speed up to rated speed) in the event of possible residual magnetism of the magnetic field. The following impacts are possible if the startup conditions are not met:

- Extreme delaying of startup and thus high thermal stressing of the motors and the upstream power system elements
- Standstill of the drive
- Tripping of the motor protection and possibly tripping of the upstream protection
- Thermal stressing of all elements in the relevant conducting path
- Synchronism loss of motors in operation down to standstill

As an extension of Fig. 4, Fig. 5 shows the envelope curve of the starting current. Similarly to activation of an inductance, on activation of the motor with the slip $s = 1$ a transient inrush current arises which then changes over to the quasi-stationary starting current. This current initially drops very slowly and does not decrease fast to the normal operating current until near the rated slip.

The starting factor (k_{st} = 3 …**6**…10) is often specified to characterize starting of machines. It essentially depends on the design (see Section 2 and Fig. 2). The restart factor ($k_{r\text{-}st}$ = 1…**3**…10) depends not only on the design, but considerably also on the speed and the still remaining magnetic field at the time of reactivation.

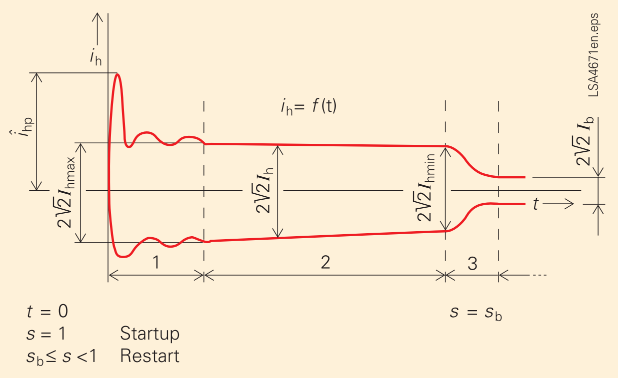

Fig. 5 Envelope curve of the starting current

$$k_{st} = \frac{I_{start}}{I_N} \quad \text{or} \quad k_{r\text{-}st} = \frac{I_{restart}}{I_N} \tag{15}$$

Fig. 6 shows the dependence of the restart factor on the slip by way of example with reference to asynchronous motors with different starting factors.

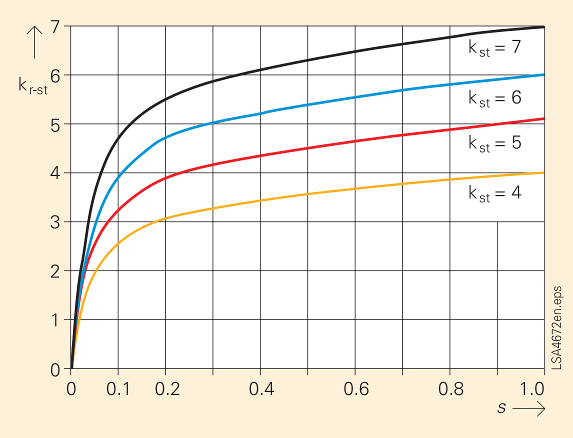

Fig. 6 Restart factor $k_{r\text{-}st}$ as a function of slip and for different starting factors k_{st}

For every drive, the starting or restarting condition is met if, at any time, the motor's torque M is greater than the resistance torque M_r (opposing torque of the machine, which is the sum of friction moments and other losses). A safety factor of 10 % is reckoned with. The required minimum voltage can be determined by applying equation (16). This lies in the order of magnitude of V_{min} = (0.55 … **0.7**) $V_{N,M}$.

$$V_{min} = V_{N,M}\,\frac{n_{pull}}{n_N}\sqrt{\frac{1.1\,M_N}{M_{pull}}} \tag{16}$$

where:

$V_{N,M}$	rated motor voltage
M_N	rated resistance torque
M_{pull}	pull-out torque
n_{pull}	pull-out speed
n_N	rated speed

An equivalent power system circuit, an example of which is shown in Fig. 7, is needed to calculate the terminal voltages.

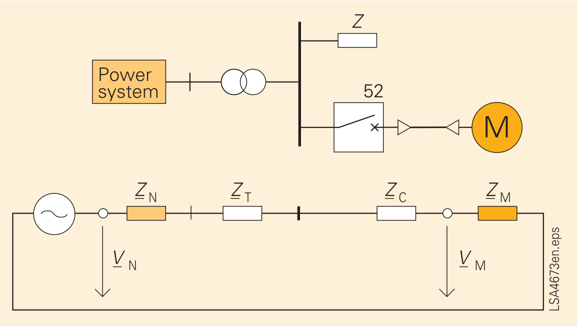

Fig. 7 Equivalent power system circuit on activation of a motor

The equivalent power system impedance $\underline{Z}_N$ is calculated on the basis of the short-circuit power, the transformer impedance $\underline{Z}_T$ from the transformer's rated data, the cable impedance $\underline{Z}_c$ from the specific cable parameters and the motor impedance $\underline{Z}_M$ from the starting factor k_{st} (see equation 17).

$$\underline{Z}_M = Z_M(\cos\varphi_A + j\sin\varphi_A) \tag{17}$$

$$\text{where } Z_M = \frac{V^2_{N,M}}{k_{st}\, S_{N,M}}$$

where:

$V_{N,M}$	rated motor voltage
$S_{N,M}$	rated motor apparent power

For high-voltage motors, a phase angle of 90° can be used for calculation to simplify matters, so that $\underline{Z}_M \approx j\,X_M$ is set.

4. Operating modes of asynchronous motors

The mechanical and thermal stresses depend on the load state of motors. During *continuous operation*, the temperature rise must not exceed the permissible overtemperature limit for the insulation system used. It is obvious that a motor may be subjected to a higher load for a certain period of time without the winding overtemperature exceeding its permissible value. After that, it is imperative to take a break for cooling down before the motor is loaded again. In IEC 60034, such operating cases have been standardized in an idealized form as so-called **duty types** S1 to S10.

S1	Continuous running duty
S2	Short-time duty (e.g. S2 60 min)
S3	Intermittent periodic duty (operation with similar loading cycles)
S4	Intermittent periodic duty with starting
S5	Intermittent periodic duty with electric braking
S6	Continuous operation periodic duty
S7	Continuous operation periodic duty with electric braking
S8	Continuous operation periodic duty with related load/speed changes
S9	Duty with non-periodic load/speed variations
S10	Duty with discrete constant loads and speeds

The predominant duty type of motors is continuous duty (approximately 90 % of all applications).

Fig. 8 shows a selection of duty types. Besides the overtemperature curves, it also shows the losses and the speed, with the result that the characteristics of the individual duty types can be derived from the depictions alone.

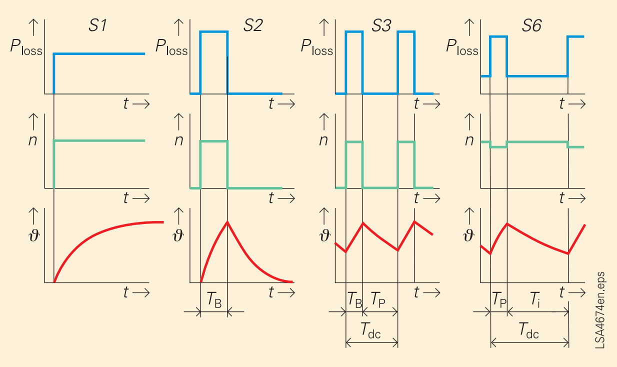

Fig. 8 Losses P_{loss}, speed n and the overtemperature ϑ for the duty types S1, S2, S3 and S6 (T_B loading duration, T_P pause duration, T_{dc} duty cycle, T_i idle duration)

5. Loss of synchronism of synchronous motors

Equation (18) describes the power for stable operation of a synchronous three-phase motor.

$$P_{mech} = P_{syn} = 3\frac{EV}{X_d}\sin\delta + \frac{3}{2}V^2\frac{X_d - X_q}{X_d\,X_q}\sin 2\delta$$

where:

P_{mech}	mechanical power output
P_{syn}	active power consumed electrically
E	rotor voltage
V	terminal voltage (phase voltage)
X_d	synchronous direct-axis reactance
X_q	synchronous quadrature-axis reactance
δ	rotor angle

If, in accordance with equation (18), the terminal voltage or the excitation voltage is reduced at a given constant mechanical power, the rotor angle δ increases until the motor falls out of step when the limit angle ($\delta > 90°$ at $X_d = X_q$) is exceeded. The motor falls out of step, no longer runs at synchronous speed.

If the power system is undisturbed, this case is encountered whenever the excitation is too low for the required mechanical power or fails completely. In this case we speak of *"loss of synchronism due to underexcitation"*. However, loss of synchronism can also occur as a result of a power system fault in which the terminal voltage drops for a short time or disappears entirely and then returns. When the voltage returns despite full excitation, the synchronizing torque cannot suffice to re-establish synchronism of the motor. In this case we speak of *"loss of synchronism due to a power system fault"*.

We can distinguish between two possibilities when a motor is not running synchronously:

1. Motor operation is stable

- with the excitation circuit closed like an asynchronous motor with two rotor windings (excitation and damper circuit) in the longitudinal axis (double-cage characteristic), but only one rotor winding (damper circuit) in the transverse axis (single-cage characteristic)
- with the excitation circuit open like an asynchronous motor with one rotor winding (damper circuit) with a single-cage characteristic

2. The pull-out point for stable asynchronous running is exceeded and the motor is braked depending on the torque characteristic of the load machine. It slips and generally comes to a standstill.

Equation (18) no longer applies to mathematical treatment of non-synchronous operation. Instead, the complete equation of motion must be applied for an oscillatory machine.

Below, the response of motors to the two failure mechanisms is discussed on the basis of a dynamic power system calculation program:

a) Loss of synchronism due to underexcitation

If the excitation voltage of a fully loaded synchronous motor is deactivated, synchronous running is no longer guaranteed and the motor loses synchronism.

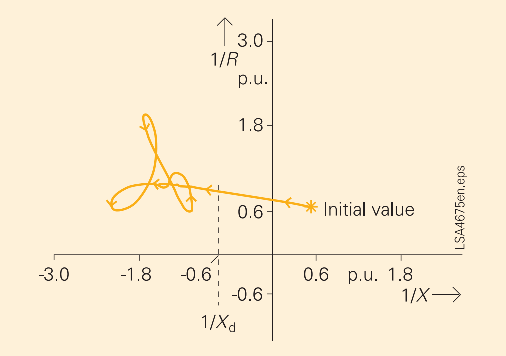

Fig. 9 Admittance in the event of excitation failure (2.22 MVA motor)

Fig. 9 shows the measured values in the admittance diagram. Due to the adequately high asynchronous pull-out torque, the motor is capable of largely stable output of the required mechanical power as asynchronous power with low slip. By contrast, the differing reactance values in the longitudinal and transverse axes result in considerable oscillations of the conductance and susceptance or the active and reactive power. In this specific case, the speed of the motor oscillates around an average of 0.99 n_{syn} with an amplitude of 0.02 n_{syn}.

Oscillation is repeated cyclically and the pull-out limit of the "asynchronous motor" is not exceeded. In all cases, the susceptance remains higher than $1/X_d$.

Excitation failure (shorted excitation circuit) was also simulated on a second motor with other data (see Fig. 10).

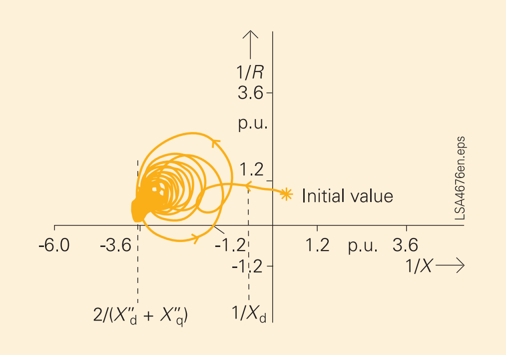

Fig. 10 Admittance in the event of excitation failure (9.88 MVA motor)

In this case the asynchronous pull-out torque is exceeded and the motor comes to a standstill at a speed of about d*n*/d*t* = 7 %/s as the slip rapidly increases. The rotor angle change rises from 600°/s to ever increasing values.

Due to differing input reactance values in the longitudinal and transverse axes, the admittance moves almost in circles. The circle diameters become increasingly smaller because, in terms of their synchronous values, these reactance values decrease towards their sub-transient values with increasing slip. The final point of this phenomenon is reached at a conductance of almost zero and a susceptance of approximately $2/(X_d'' + X_q'')$.

b) Loss of synchronism due to short-time power system voltage failure

In the event of a three-phase power system short-circuit and a related breakdown of the power system voltage, a synchronous motor can no longer obtain the mechanical power required by the load as electrical power from the power system. The lacking power is covered by the (negative) acceleration power. As this is proportional to the change in the rotor angle's rate of rise ($d^2\delta/dt^2$), a fast rotor angle change is enforced. In this case, the rotor angle is understood to be the angle between the rotor voltage and the power system voltage at an unchanging frequency. After short-circuit tripping and the related return of voltage, either resynchronization or a loss of synchronism can occur depending on the motor constant, the mechanical load and the short-circuit duration.

Fig. 11 shows the circle diagram, with the motor just not having lost synchronism. Although the speed drops to 5 % and the rotor angle has almost reached 180° in the time without voltage, the synchronizing torque after the voltage returns is high enough for the motor to resynchronize.

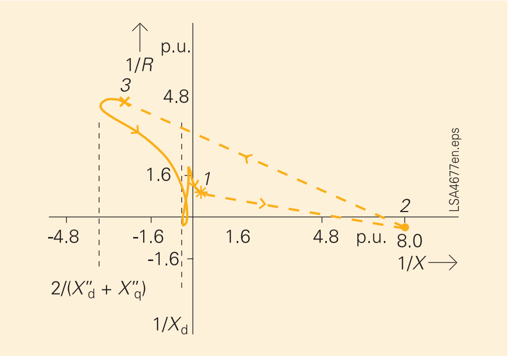

Fig. 11 Circle diagram of the admittance due to a three-pole short-circuit lasting 0.15 s (2.22 MVA motor)
1 – Initial value
2 – Value during the short-circuit
3 – Value after short-circuit tripping

Extension of the short-circuit duration by 50 ms leads to a greater speed drop (8 %) and the motor loses synchronism (see Fig. 12). Similarly to the underexcitation shown in Fig. 10, the circle diagram shows circular motions around the point $1/Xd''$. As the full excitation is effective, the circle diameters are accordingly larger. Here also, the susceptance always remains higher than $1/X_d$.

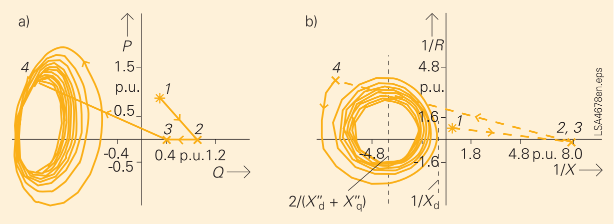

Fig. 12 Circle diagram of the admittance due to a three-pole short-circuit lasting 0.2 s (9.88 MVA motor)
a) Power circle diagrams
b) Admittance circle diagrams
1 – Initial valus
2 – Value at the start of the short-circuit
3 – Value on short-circuit tripping
4 – Value after short-circuit tripping

c) Conclusion

The examples clearly show that loss of synchronism of synchronous motors can be coped with very well by means of underexcitation protection with an admittance characteristic (see 7UM61 or 7UM62 manuals). Only one protection characteristic is needed, which must be set to $1/X_d$. An adequate delay should be set to give the motors an opportunity to resynchronize. During simulation runs, this resynchronization took no more than 0.5 s in the worst case of motor stressing at rated load. Therefore, a tripping delay of 1 s is recommended for loss of synchronism.

As the motor terminal voltage changes only slightly due to the mostly low input reactance, reactive power monitoring can also be used as an alternative.

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Overview of Protection Functions and Protection Relays for Motors

In this chapter, suitable protection functions are discussed on the basis of possible faults in asynchronous and synchronous motors. An overview follows, showing how protection functions are distributed over individual protection relays. To conclude, the basic use of protection facilities for the various motor types and power classes is discussed.

1. *Faults and protection functions*

With motors, various causes of faults are possible. Table 1 shows an overview of essential causes of faults and their influences. For both the stator and the rotor, thermal overloading plays a central role. Such inadmissible stressing has a general influence on the useful life of a motor and leads to premature aging. This, in turn, has a detrimental influence on insulation capacity and simultaneously increases the probability of follow-up faults which can consist of earth faults and short circuits.

Cause	Fault type				
	Thermal overload	Interwinding fault (2-pole, 3-pole)	Earth fault	Interturn fault	Mechanical destruction
Insulation aging		●	●	●	
Stationary and transient overvoltages		●	●	●	
Undervoltage	●				
Asymmetrical voltage	●				
Conductor discontinuity, phase failure	●				
Asynchronous changeover	●				●
Bearing damage	●				●
Mechanical overload during continuous operation	●				
Inadmissibly long starting time	●				
Rotor locking during starting	●				
Inadmissibly short pause time, too frequent reclosing	●				
Soiling	●				
Inadmissibly high ambient temperature	●				
Cooling failure	●				

Table 1 Overview of causes of faults and types of faults in asynchronous motors

Fault	Protection functions	ANSI
Thermal overloading of the stator due to overcurrent, cooling problems, soiling, etc.	– Thermal overload protection with complete memory – Measurement of stator temperature by temperature sensor (e.g. PT100)	49
Thermal overloading of the rotor during starting – Too long, rotor locked – Too frequent	Overload protection by two principles – Starting time supervision – Restart inhibit	 48 66, 49R
Voltage asymmetry, phase failure	Negative-sequence protection (definite-time; thermal stage)	46
Overloading and thus overtemperature of the bearings	Measurement of bearing temperature by temperature sensor (e.g. PT100)	38
Overstressing of drives running idle (pumps or compressors)	Minimum power consumption – Undercurrent $I<$ – Active power $P<$	 37 32U
Earth fault	– Earth-fault signaling via displacement voltage – Earth current measurement (motor connected by short cables) – Earth-fault direction	59N 51Ns 67Ns
Short circuits	– Time-overcurrent protection – Differential protection	50, 51 87M
Undervoltage	Undervoltage protection (definite-time, inverse time)	27
Excitation failure in the case of synchronous motors	Underexcitation protection	40
Asynchronous running of synchronous motors (falling out of step)	Underexcitation protection	40

Table 2 Allocation of protection functions to types of faults

Causes of faults such as hidden manufacturing faults, assembly errors (e.g. motor distortion or one-sided bearing pressure when connecting the machine) and inadequate maintenance are not listed.

The task of protection consists of

- safeguarding the motor against destruction in the event of a thermal overload and thus against a reduction of its useful life.
- sufficiently fast deactivation in the event of any short circuits, earth faults and interturn faults, both counteracting expansion of the damage to the motor (destruction of the core assembly or motor burning) and limiting the impact on other connected loads (voltage symmetry, voltage drops and current overloads).

Table 2 lists the relationships between possible faults and protection functions that detect these faults.

An overcurrent protection that detects mechanical faults, above all in the drive machine, is not listed. Here, for example, it is conceivable that bulk goods in coal mills get stuck, induced draft ducts clog up or mechanical damage occurs. The resulting overcurrent inevitably leads to overloading of the motor and calls for tripping by the overload protection. If heating time constants are long, tripping is delayed accordingly.

To additionally reduce stress and strain on the motor, an overcurrent protection with a timer element (approximately 1 s delay) is used in the case of current clearly above the rated level (e.g. 2 $I_{N,M}$). This protection function is inactive during starting. If short circuits occur during normal operation, this function also acts as short-circuit protection in a clearly shorter time.

A detailed discussion of the individual protection functions is dispensed with because these are discussed in other chapters.

2. *Scope of protection functions provided by the protection relays*

Protection function	ANSI	7SJ602	7SJ61	7SJ62	7SJ63/64	7UM61	7UM62
Analog inputs		$3I$, I_{ee}	$3I$, I_{ee}	$3I$, I_{ee} $3V$	$3I$, I_{ee} $3V/4V$ 2TD/-	$3I$, I_{ee} $4V$	$6I$, $2I_{ee}$ $4V$ 3TD
Stator overload protection	49	●	●	●	●	●	●
Starting time supervision, locked rotor protection	48	●	●	●	●	●	●
Restart inhibit	66, 49R	●	●	●	●	●	●
Negative-sequence (unbalanced-load) protection $I_2 >$	46	●	●	●	●	●	●
Thermal unbalanced-load protection ($I_2^2\, t$)	46					●	●
Temperature monitoring (via RTD-box)	38	● 1)	●	●	●	●	●
Undercurrent protection	37	●	●	●	●	●	●
Active power protection ($P <$)	32U					●	●
Earth-fault protection	59N,			●	●	●	●
Non-directional	51Ns	●		●	●	●	●
Directional	67Ns	● 2)	●	●	●	●	●
Overcurrent protection	50, 51	●	●	●	●	●	●
Current differential protection	87M						●
Undervoltage protection	27			●	●	●	●
Overvoltage protection	59			●	●	●	●
Underexcitation protection	40					●	●
Rotor earth-fault protection	64R					●	●
Frequency protection	81		●	●	●	●	●
Breaker failure protection	50BF	●	●	●	●	●	●
Freely programmable logic (PLC/CFC)			●	●	●	●	●
Control function			●	●	●	●	●
Graphics display					●		●
Flexible interfaces		1	2	2	2/3	2	3
Frequency operating range (11 Hz – 69 Hz)						●	●
Operational measured-values		●	●	●	●	●	●
Event log and trip log		●	●	●	●	●	●
Oscillographic records		●	●	●	●	●	●
Protocols		MODBUS PROFIBUS-DP IEC 60870-5-103	MODBUS PROFIBUS-DP DNP 3.0 IEC 60870-5-103 IEC 61850	MODBUS PROFIBUS-DP DNP 3.0 IEC 60870-5-103 IEC 61850	MODBUS PROFIBUS-DP DNP 3.0 IEC 60870-5-103 IEC 61850	MODBUS PROFIBUS-DP DNP 3.0 IEC 60870-5-103	MODBUS PROFIBUS-DP DNP 3.0 IEC 60870-5-103 IEC 61850

Table 3 Motor protection functions in the SIPROTEC protection relays
(I_{ee} – sensitive current input, TD – measuring transducer);
Note on 7SJ602:
1) Depending on the order – not available if communication protocol needed
2) Optional ordering also possible with V_e

Scope of protection functions provided by the protection relays

In particular, numerical protection is noted for its multiple functionality. Depending on the application, various protection functions can run on one item of standard hardware. Regardless of whether a cable, an overhead line, a generator or a motor is being protected, we are always dealing with the same device type. This simplifies engineering by means of an identical amount of hardware. Applications can be standardized and the need for spare parts can also be reduced.

In addition to choosing the hardware, users must order the appropriate combination of protection functions.

Table 3 provides an overview of the functions for motor protection applications integrated in the protection units and a selection of additional functions is listed.

■ 3. Use of the protection relays

The scope of protection to be applied depends essentially on the rated power of the motor, its mode of operation and its role and importance in terms of the technological process linked to it. It goes without saying that costs also have to be considered. Total costs should be considered because, to some extent, the costs of repairing a motor are relatively low in comparison with the repair costs of other electrical equipment. In case of a failure, however, the follow-up costs for the production system often amount to a multiple of the repair costs.

The overview in Fig. 1 shows a breakdown of protection units according to power classes of motors and applies to asynchronous motors. The preferred types of protection relays are listed in the left-hand column.

If additional functions are required, for example freely programmable logic, more scope for serial communication, a wide frequency operating range and much more, refer to the units in the right-hand column. As the majority of protection units are installed directly in the medium-voltage cubicle, increased use is being made of control function. Here, the relays with graphics display offer advantages in the form of illustration of a feeder with the switching devices. The conventional mimic diagram can be dispensed with.

Table 4 describes the advantages of the optional relays from Fig. 1.

Classification	Options
Low (100 – 500 kW)	**7SJ61:** more functions (e.g. PLC/CFC), more communication scope, and more binary I/Os
Medium (500 kW – 2 MW)	**7SJ63/64:** graphics display and thus better local control, scalable binary I/O quantities; 7SJ64 has higher PLC/CFC performance and one additional interface. **7UM61:** larger volume of binary I/Os, wider frequency range (reliable protection functionality even during running down of a motor)

Table 4 Explanation of the options

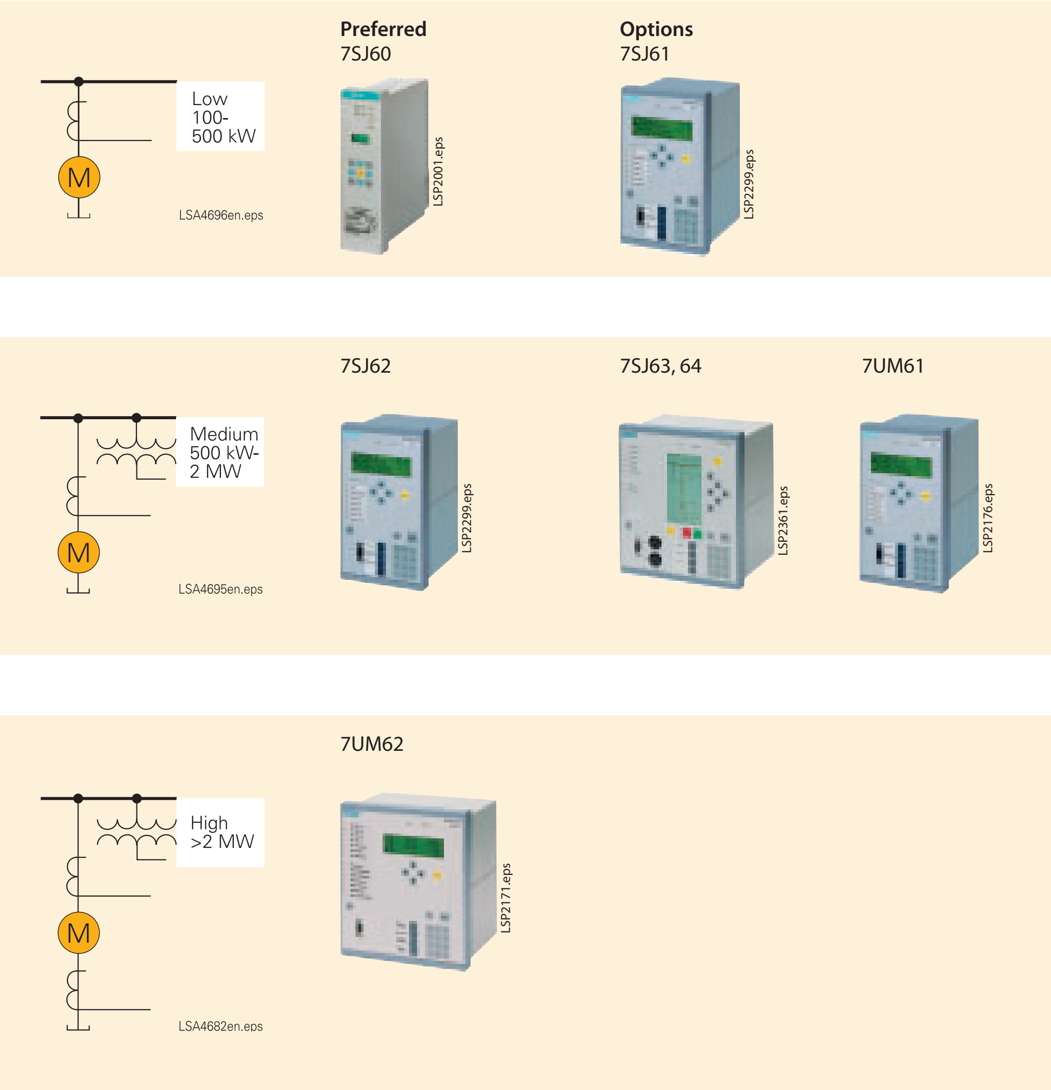


Fig. 1 Allocation of protection relays to motor power classes

The power of synchronous motors is generally clearly higher than 2 MW. This is why it is imperative to provide differential protection.
A SIPROTEC 7UM62 with the "Generator Basic" option is recommended as the protection unit. This option features underexcitation protection to detect excitation problems (failure or regulation problems) and out-of-step cases (loss of synchronism).

You will find further notes on application, connection and setting of the protection relays in the following chapters.

Thermal Stress of Motors and Necessary Protection Functions

Thermal stress of motors is discussed in this chapter. The various operating states are considered and the thermal influence is derived from them. The second part contains discussions of suitable protection principles and a basic explanation of their implementation in the numerical protection unit. Taken from motor data sheets, notes on setting the protection functions are provided.

■ 1. Heating phenomena

In the process of conversion from electrical to mechanical energy, losses occur which leads to equipment heating up, i.e. a motor. Their design permits certain thermal stress.

Heating sets in when the heat sources become effective. The fed energy is first of all stored in each volume element as heat. The initial curve of the temperature rise $\vartheta = f(t)$ is independent of the thermal resistors through which the heat is later dissipated. Moreover, it is in no way identical everywhere because different loss density values prevail in the various windings and also in the individual segments of the magnetic circuit. The motor can therefore generally not be looked upon as a homogeneous-body system.

Temperature differences develop between the parts of the motor and with respect to the surrounding coolant, and heat begins to flow in the direction of the coolant. The temperature difference between the coolant (which can also be air) and the machine part is called *temperature rise* (or overtemperature). After an adequately long time, the heat flows reach a state of equilibrium. Then, heat is no longer stored. The temperature has reached its *temperature-rise limit value.* Fig. 1 shows how the *temperature rise* (or overtemperature) develops for characteristic points within the stator of a motor.

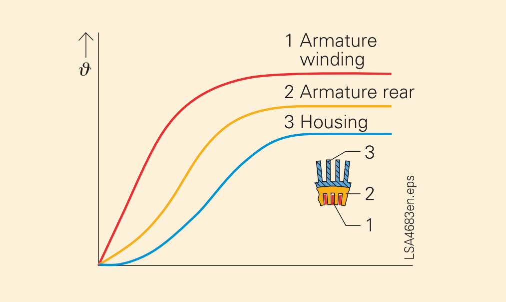


Fig. 1 Temperature rise at three characteristic points on the stator

The *permissible temperature rise* of an electric machine is primarily limited by the relatively low thermal resistance of the insulators for the windings. The insulation systems are subdivided into *temperature classes A to H* in relation to their thermal resistance. The permissible temperature rise of a winding at its hottest point differs from the permissible temperature of the insulation system used by the agreed maximum temperature of the coolant (ambient temperature), which is defined as 40 °C. A safety factor of 5 to 15 K is generally also added.

Two modes of operation must be distinguished when considering a motor from the point of view of thermal influences.

a) Normal operation under load

Depending on the torque to be applied, the corresponding current is picked up from the power system which, depending on the design, leads to the heat development described above. We can refer mainly to the stator. The motor manufacturer defines a machine thermally for the permissible temperature class. Operation under rated conditions leads to a temperature rise that can generally be assigned to a lower temperature class. For example, if you find the letters F/B (designed/operated) in the motor data, the motor is designed for the temperature class F, but is used in accordance with temperature class B. These thermal reserves results in a continuous overload capacity of about 10 %. A higher overload is possible for a brief time, but the manufacturer does not specify any data because of the various influencing parameters. The thermal withstand curve (see Fig. 2) is to be referred to.

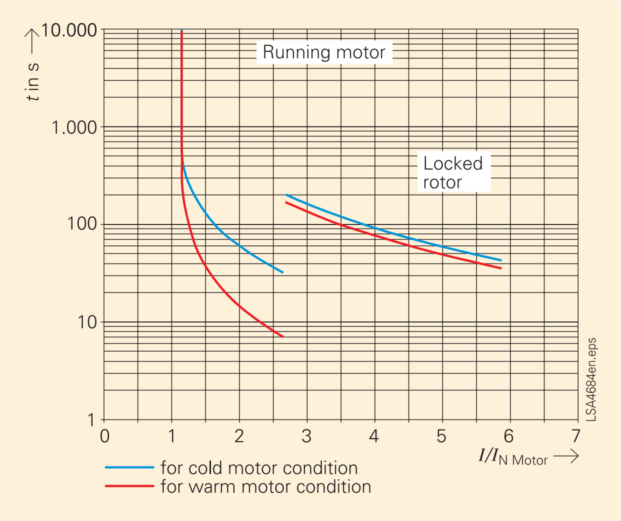


Fig. 2 Maximum permissible thermal overload of a motor

(Thermal copper time constant (short-time duty):	2.7 min
Thermal time constant (continuous duty (S1)):	15 min
Cooling time constant at standstill:	105 min
Temperature class (designed/operated):	F/B

The curves are specified for when the motor is both cold and warm. Warm means that the motor has been operated with rated quantities and an overload then occurred. The graphic above shows the worst case, the curve of the copper time constant for short-time duty. The time constant for continuous duty must be used for the protection setting. The continuously permissible current can also be found in the characteristic. According to Fig. 2 this is approximately 1.15 $I/I_{N,M}$.

In the American (NEMA) region, the overload is described by the service factor (SF), which specifies the permissible overload for the rated power in the S1 mode. This overload refers to the overall system (electrical and mechanical parts). According to NEMA MG1, the permissible limit overtemperatures of the relevant temperature class may be 10 K higher. The values for the service factor lie, for example, at 1.1, 1.15, etc. However, if SF = 1 is specified, this means that the motor may only be operated at the rated power. Thermal overload protection refers only to the motor winding. If SF = 1 is specified, a continuously permissible winding overcurrent of 10 % can be assumed because the insulation is generally designed in accordance with temperature class F and the motor is mainly operated in accordance with temperature class B. If SF = 1.1, this may be more than 10 % (e.g. quite possibly 15 %). Refer to the thermal characteristic for the exact value of the continuously permissible overload current (see Fig. 2).

For detection of temperature rise, two temperature sensors (preferable PT100) are usually installed for each phase in the stator winding. Motor manufacturers have placed them at the thermally critical points. The tripping temperature can be derived from the temperature class. F signifies a maximum permissible temperature of 155 °C and for B the value lies at 130 °C. The latter temperature ought to set in approximately when the motor is loaded with rated quantities. Minus a safety factor of 10 K, the tripping value is approximately (155 °C -10 K = 145 °C).

The rotor additionally heats up when the motor is operated on an ***asymmetrical voltage***. The most critical case is discontinuity in a phase. Voltage asymmetry means that there is a negative-sequence voltage system that is driving a negative-sequence current. This negative-sequence rotating field leads to an AC current in the rotor (100 Hz relative velocity) in the opposite direction of rotation. Due to the skin effect, a larger rotor resistance takes effect which, in turn, leads to increased heating up. It can be assumed that 1 % negative-sequence system voltage leads to about 5 % to 6 % negative-sequence system current.

The stator current can be estimated by way of the equivalent circuit. It must be split into the positive phase-sequence and negative phase-sequence systems. As the rotating field of the negative-sequence system runs in the negative direction at the synchronous speed, the slip for the negative-sequence system is 2-s. The influence of the different rotor resistance values is very easily recognizable in Fig. 3.

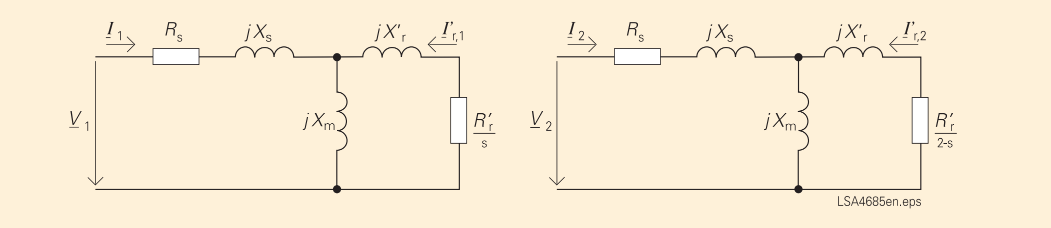


Fig. 3 Equivalent circuit diagram of a motor as positive and negative-sequence systems (left: positive-sequence system, right: negative-sequence system)

Unless otherwise specified, it can be approximately assumed that about 2 % negative-sequence system voltage does not lead to any additional heating of motors. This corresponds to a continuously permissible negative-sequence system current of approximately 10 %. If the current rises above this value, tripping must take place after defined times. Unfortunately, motor manufacturers seldom specify any data in this respect.

b) Starting

During starting, thermal stress occurs in the rotor due to the starting currents. Typical starting phenomena are dealt with in the first chapter entitled “Introduction to the principles of asynchronous and synchronous motors”.

The cases of the locked rotor and the accelerating rotor must basically be considered. In the case of motors with critical rotors (the majority of them), the locked rotor case constitutes the higher stress from the thermal point of view. This is why motor manufacturers frequently specify the thermal limits of the locked motor in the thermal limit curve. These curves are shown on the right in Fig. 2. If the motor accelerates, the thermal limits are generally above them.

The motor’s starting time, for both the rated voltage and the 80 % case, is also found in the technical data. These times apply on connection of the machine.

For example, the motor’s starting time is 24.0 s with a starting current of 5.6 I/I_N under rated voltage conditions (V_N) and 52 s at 4.17 I/I_N and 0.8 V_N. In Fig. 2, we read a time of about 40 s for the warm condition at 5.6 I/I_N, with the result that the characteristic of starting time monitoring can lie below the locked rotor characteristic.
A speed check is not imperative here.

A further thermal stress results from the frequency of successive ***startups*** of the motor. Here, manufacturers distinguish between warm and cold. We frequently find the typical value of three startups from the cold state and two startups from the warm state. This statement also applies to starting with a reduced voltage (80 %).

A further important characteristic quantity is the number of permissible startups per year. This amounts to 1000, for example, and must not be exceeded.

■ 2. Implemented protection configurations

2.1 Stator thermal overload protection (normal duty)

In Section 1, we worked out that temperature response is complex and really ought to be described by a thermal network. This description leads to differential equations of a higher order, for which the input parameters are missing, however. Due to the limited availability of data from motor manufacturers, the simplified description based on a homogeneous-body model has established itself. Fig. 4 shows the model with the heat source, realized as the current source I^2, heat storage in the capacitor C_{th}, heat dissipation through the resistor R_{th} and the ambient temperature ϑ_a. The model is based on a reference temperature ϑ_0 of 40 °C. The temperature ϑ describes the motor’s overtemperature.

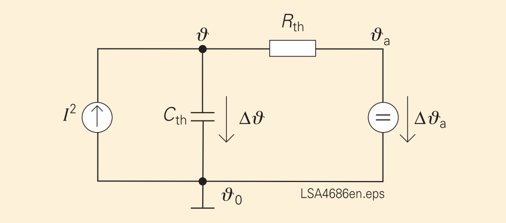


Fig. 4 Equivalent circuit diagram of the thermal model

The following differential equation (1) can be derived from the equivalent circuit diagram, which is simplified further when we assume a constant reference temperature ϑ_0.

$$I^2 = C_{\mathrm{th}} \frac{\mathrm{d}(\vartheta - \vartheta_0)}{\mathrm{d}t} + \frac{\vartheta - (\vartheta_{\mathrm{a}} - \vartheta_0)}{R_{\mathrm{th}}} \rightarrow$$

$$I^2 R_{\mathrm{th}} = R_{\mathrm{th}} C_{\mathrm{th}} \frac{\mathrm{d}\vartheta}{\mathrm{d}t} + \vartheta - (\vartheta_{\mathrm{a}} - \vartheta_0) \qquad (1)$$

When a constant ambient temperature is assumed, the maximum permissible current will lead to the maximum permissible temperature ($I^2_{\max} \cdot R_{\mathrm{th}} \triangleq \vartheta_{\max}$). If we scale equation (1) with the maximum permissible quantities, we arrive at the differential equation to be implemented in the program. The differential equation must be calculated separately for each phase current. Tripping occurs if the value 1 is reached in at least one phase (reason: calculation is based on scaled quantities).

$$I^2_{\mathrm{p.u.}} = \tau_{\mathrm{th}} \frac{\mathrm{d}\Theta}{\mathrm{d}t} + \Theta - \Theta_{\mathrm{a}} \qquad (2)$$

with the following scaling

$$I_{\mathrm{p.u.}} = \frac{I}{I_{\max}} = \frac{I}{\mathrm{k} I_{\mathrm{N}}} \qquad \Theta = \frac{\vartheta}{\vartheta_{\max}} = \frac{\vartheta}{\mathrm{k}^2\, \vartheta_{\mathrm{N}}}$$

$$\tau_{\mathrm{th}} = R_{\mathrm{th}} C_{\mathrm{th}} \qquad \Theta_{\mathrm{a}} = \frac{\vartheta_{\mathrm{a}} - \vartheta_0}{\vartheta_{\max}} = \frac{\vartheta_{\mathrm{a}} - \vartheta_0}{\mathrm{k}^2\, \vartheta_{\mathrm{N}}}$$

The solving of the differential equation leads to the well-known exponential expression. If the current is increased abruptly, the temperature exponentially approaches the stationary value.

$$\Theta(\mathrm{t}) = (I^2_{\mathrm{p.u.}} + \Theta_{\mathrm{a}} - \Theta_{\mathrm{t=0}})\left(1 - \mathrm{e}^{-\mathrm{t}/\tau_{\mathrm{th}}}\right) + \Theta_{\mathrm{t=0}} \qquad (3)$$

As all values are scaled, the tripping time when $\Theta(\mathrm{t}) = 1$ is set can be calculated on the basis of equation (3). If we also use the scaling quantities of equation (2) and assume a measured ambient temperature, the tripping time can be calculated with the following equation. If no ambient temperature is measured, $\vartheta_{\mathrm{a,\,measured}} = 40$ °C must be inserted and this leads to further simplification of equation (4).

$$t = \tau_{\mathrm{th}} \cdot \ln \left(\frac{\frac{1}{\mathrm{k}^2}\left(\frac{I}{I_{\mathrm{N}}}\right)^2 - \frac{1}{\mathrm{k}^2}\left(\frac{I_{\text{previous load}}}{I_{\mathrm{N}}}\right)^2}{\frac{1}{\mathrm{k}^2}\left(\frac{I}{I_{\mathrm{N}}}\right)^2 + \frac{1}{\mathrm{k}^2}\left(\frac{\vartheta_{\mathrm{a,measured}} - \vartheta_0}{\vartheta_{\mathrm{N}}}\right) - 1} \right)$$

A quasi-stationary state (constant over 5 τ_{th}) is presupposed for the previous load and the measured ambient temperature.

Therefore, for overload protection, two characteristic quantities of the motor are needed, the factor **k**, which describes the continuously maximum permissible current referred to the rated current, and the thermal time constant τ_{th}. If the ambient/coolant temperature is measured, the temperature that sets in under the rated conditions is also needed as a scaling quantity. If this is not available, it can be measured via the temperature sensors.

During operation with a different load, the heating time constant is equal to the cooling time constant. Longer cooling (no forced cooling by the fan) must be assumed if the motor is shut down, however. If, in this process, the current falls below a minimum value, standstill can be assumed and it is possible to switch over to the longer cooling time constant (in the example shown in Fig. 2, this is 105 min).

The behavior of the thermal model on activation of the motor must now also be considered. Here, however, the thermal load acts on the rotor. This signifies restricted validity of the stator model or of the setting values. Two strategies are currently pursued:

- *Freezing the thermal memory during starting*
  This is intended to avoid overfunction of the overload protection during starting.
- *Internal limiting of the starting current*
  The current fed to the thermal model is limited during starting. This "slows down" heat development. Current limiting should lie at approximately 2.5 $I/I_{\mathrm{N,M}}$ (see also Fig. 2). Further reduction of limiting is recommended if starting times are long and successive warm starts are possible. In the example, a value of 2 $I/I_{\mathrm{N,M}}$ makes sense for a starting time of 52 s (at 0.8 V_{N}).

Different operating states were assumed to provide an insight into the thermal behavior of the thermal model. Fig. 5 encompasses the following sequence: starting with rated voltage (starting time = 24 s), continuous duty under rated conditions, deactivation and direct reactivation at a reduced voltage (starting time = 52 s), brief duty with a reduced load (0.9 $I/I_{\mathrm{N,M}}$) and then shutdown of the motor. After shutdown we recognize the effect of the longer cooling time constant very well. During starting, the starting current for the thermal model was limited to 2 $I/I_{\mathrm{N,M}}$.

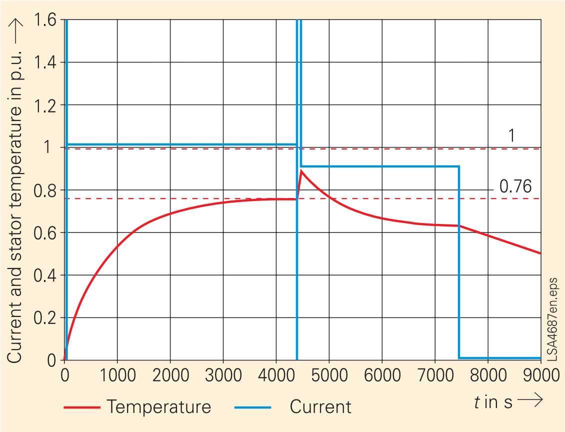


Fig. 5 Behavior of the model in different load cases (data: k = 1.15; $\tau_{heating}$ = 15 min; $\tau_{cooling}$ = 105 min)

The tripping threshold for the thermal model is 1 (corresponding to 100 %). The higher, but already reduced, current leads to a visible temperature increase during starting. However, the tripping threshold is not reached despite the long starting time. During operation under rated conditions ($I = I_{N,M} = 1$), the thermal memory has a "filling level" of about 76 % (rule of proportion: 1.15^2 / 100 % like 1^2 / x %).

2.2 Thermal protection with an asymmetrical voltage (unbalanced-load protection)

Voltage asymmetry leads to a current asymmetry, which can be described by the negative-sequence system current. On the basis of the phase currents, the protection algorithm calculates (corresponding to the definition equation of the symmetrical components) the negative-sequence system current that is to be assessed in protection terms. In the simplest case, thresholds are queried and tripping is initiated after a set delay.

To take the heat development process into account, an I_2^2t characteristic must be simulated, which is a well-known characteristic (e.g. $I_2^2\,t$ = 10 s) in synchronous machines. The characteristic is released when the permissible negative-sequence (unbalanced-load) threshold (e.g. 10 %) is exceeded. Below the threshold, the motor must be allowed to cool down. An inverse curve results as the tripping characteristic (see also Fig. 9).

2.3 Starting time supervision

The rotor is thermally overloaded if starting is too long. The thermal limit (see Fig. 2) is described by an I^2t characteristic. This characteristic must be simulated. The following equilibrium condition (see equation (5)) can be set up and the permissible starting or blocked-rotor time can be determined on the basis of it.

$$I^2\,t = I^2_{\text{start}}\,t_{\text{start}} \rightarrow t = \left(\frac{I_{\text{start}}}{I}\right)^2 t_{\text{start}} \qquad (5)$$

where:

I_{start}	maximum permissible starting current
t_{start}	maximum permissible starting time
I	measured starting current

Tripping occurs if the actual time is longer. The tripping characteristic has an inverse character and adapts very well to the starting conditions (with rated voltage and reduced voltage).

The calculation in accordance with equation (5) is not released until starting is detected. For typical motors, the necessary current threshold amounts to approximately 2.5 $I_{N,M}$. The threshold must be lowered accordingly for motors with reduced starting currents.

By way of example, Fig. 6 shows starting currents/times measured for a motor. Adaptation of the protection characteristic to the starting conditions is easily recognizable.

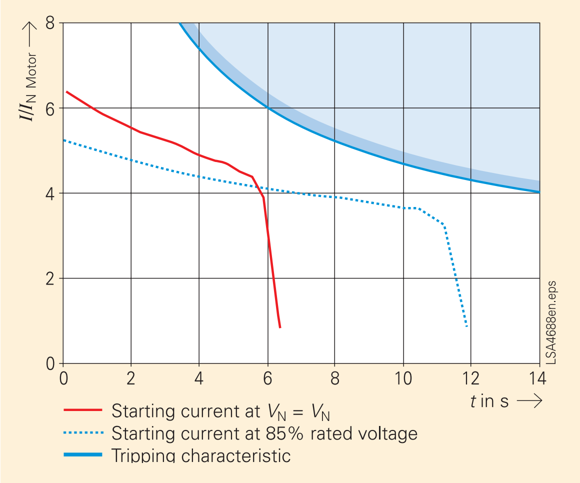


Fig. 6 Measured starting currents and tripping characteristic

2.4 Restart inhibit

Inadmissible heating of the rotor occurs when the motor is started too many times in succession. In the simplest case, the permissible limits can be monitored by counter and the specified pause times can then be kept to.

Another approach is to model heating of the rotor to determine the thermal limit for the permissible restarts. In this way, we get closer to the physical conditions and can generally load the motor better.

A homogeneous-body model is also expedient for modeling. The two necessary parameters consisting of the k factor for the rotor (k_r) and the rotor time constant τ_r must be found. Both values are generally not given. However, they can be derived from data of the manufacturers such as the number of cold starts (n_c) and warm starts (n_w), the starting time and the associated starting current. We create an equation system that describes the cold and warm states with the known quantities and we determine from it the two unknown values (k_r and τ_r). Equation (6) shows the approximated solution.

$$k_r \approx \sqrt{\frac{n_c}{n_c - n_w}} \qquad \tau_r \approx (n_c - n_w)\, I^2_{\text{start}}\, t_{\text{start}} \qquad (6)$$

These parameters calculated internally in the function are incorporated into the thermal model (by analogy to equation (2)). Restart inhibit becomes active if the thermal memory has reached a corresponding filling level. This threshold lies at $(n_c - 1)/n_c$.

At standstill, the slower cooling is taken into account by extending the time constant. Before then, the thermal replica is frozen for an adjustable time to take internal transient phenomena into consideration. Only then does exponentially decaying cooling take place. Renewed restart is prevented for this time to allow the motor to run down.

To meet demands for a minimum standstill time, an additional delay time is started after blocking by the thermal restart inhibit function. This time takes effect only if the thermal model has enabled it beforehand.

Fig. 7 shows the thermal behavior for a possible operating case. The motor is started from the cold state and runs under rated conditions for a certain time. After that, it is restarted twice from the warm state and operated at 90 % of the rated current. The number 1 describes the thermal limit for the rotor and 0.67 the restart inhibit threshold.

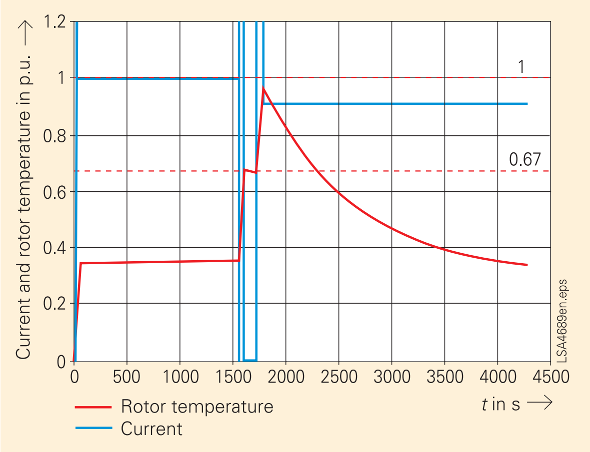


Fig. 7 Behavior under different loads according to the thermal rotor model (t_{start} = 52 s; I_{start} = 4.17 $I/I_{N,M}$; $n_c = 3$ and $n_W = 2$)

The first restart from the cold state leads to rotor heating, which will also set in during rated operation. Two restarts are permitted from this warm state. When the warm motor restarts a second time, the restart inhibit threshold is exceeded and the temperature approaches limit value 1. This value represents the maximum permissible rotor temperature. Subsequent continued operation under load conditions leads to corresponding cooling of the motor. If the motor were now deactivated, it could be restarted immediately again because there is a sufficient thermal reserve.

If, by contrast, it were deactivated immediately after the second start from the warm state, the restart inhibit function would immediately take effect and would prevent renewed restarting. From the thermal point of view, restart is only permitted when the temperature falls below the 67 % threshold.

■ 3. *Protection setting*

To summarize, the setting parameters for the thermal protection functions are gathered together in a table and are commented on briefly.

a) Stator overload protection

Setting parameters	Value	Comment
Heating time constant	15 min	Take this from the motor data sheet (see Fig. 2) or calculate it on the basis of a specified characteristic (equation (4) can be used to do this).
Cooling time constant	105 min	Take this from the motor data sheet (see Fig. 2) or set an experience-based value, e.g. 7 times the heating time constant.
k factor	1.15	Take this from the thermal characteristic; if this is not available, a k factor of 1.1 can be used (see Section 1 – temperature class F/B).
Thermal alarm stage	90 %	During operation under rated conditions, the thermal warning stage is always below 90 %. With the default setting of 1.1, this is 83 % and in the case of k = 1.15, only 76 %.
Current limiting	$2\ I/I_{N,M}$	A slightly lower value has been chosen due to the long starting time, in particular with a reduced voltage. The value 2.5 $I_{N,M}$ can be used for a short starting time.
Current alarm stage	$1.15\ I_{N,M}$	This should be set to equal the k factor.

b) Negative-sequence protection

Setting parameters	Value	Comment
Continuously permissible unbalanced-load or alarm stage	$0.1\ I_2/I_{N,M}$	Unless otherwise specified, this value should be set. If this stage should also trip, it must be delayed appropriately (approximately 15 - 30 s); suggestion: 20 s.
Tripping stage	$0.4\ I_2/I_{N,M}$	Two-phase operation under rated conditions leads to a negative phase-sequence system current of about 66 %. Due to the power to be produced, it will rise and will certainly reach values of 100 %. A tripping delay of about 3 s is recommended to allow for transient phenomena.
Thermal unbalanced-load time $((I_2/I_{N,M})^2\ t = K)$ (*Internal designation:* FACTOR K)	2 s	The conservative setting of 2 s is chosen if the motor manufacturer does not specify any details. The time really ought to be longer if an effect comparable to synchronous machines is presupposed.
Cooling time of the thermal model	200 s	Use the following relationship: $t_{\text{cooling}} = \frac{K}{\left(\frac{I_{2,\text{permiss.}}}{I_{N,M}}\right)^2} = \frac{2\ \text{s}}{0.1^2} = 200\ \text{s}$

c) Starting time supervision

Setting parameters	Value	Comment
Starting current (pickup current)	$5.6\ I/I_{N,M}$	Take this from the motor data sheet (starting curves).
Maximum permissible starting time	35 s	To this end, the specified starting times must be compared with the characteristic curve times. Go below the thermal characteristic if there is an adequate safety clearance. According to Fig. 2, a value of 40 s is permissible in the case of 5.6 $I/I_{N,M}$ in the warm state. For this current, the motor's starting time was specified as 24 s. Chosen permissible starting time: 35 s
Start detection	$2\ I/I_{N,M}$	With the voltage reduced, the starting current amounts to 4.17 $I/I_{N,M}$ and current limiting for unbalanced-load protection was also defined at 2 $I/I_{N,M}$. The typical value of 2.5 $I/I_{N,M}$ can be used for standard motors.

d) Restart inhibit

Setting parameters	Value	Comment
Starting current (pickup current)	4.17 $I/I_{N,M}$	The current in the case of the longest starting time is taken from the motor data sheet. This is the value at the reduced voltage.
Starting time	52 s	Choose the time that belongs to the current; if a motor starts clearly faster, e.g. in 2.6 s, you can be a little more generous with the setting. Here, we choose the lowest setting of 3 s.
Cold starts	3	Take this from the motor data; if values are missing, assume the value 3.
Warm starts	2	Take this from the motor data; if values are missing, assume the value 2.
Rotor temperature equalization time	1 min	This time is considered practicable and also takes running down to standstill into account. ***Note:*** Restarting of the motor is not possible during this time. The time must be set to zero if only blocking is to take place when the thermal limit is reached.
Extension of time constant at stop	5	This value is recommended for long starting times. It leads to release of the restart inhibit function after approximately 30 minutes. At least the value 10 must be chosen if the starting times are clearly slower.
Minimum restart inhibit time	30 min	A time between 15 min and 30 min is recommended if no data is available. The longer time must be chosen for longer starts.

e) Characteristics resulting from the protection setting values

By analogy to Fig. 2, Fig. 8 shows the tripping time of the thermal characteristics. The thermal overload protection characteristic can be seen on the left and the starting time supervision characteristic can be seen on the right. The locked rotor characteristic of the manufacturer is also shown (curve just above it).

Fig. 9 shows the tripping response to a negative-sequence. In addition to the thermal characteristic, the two definite-time characteristics are also shown.

Fig. 7 adequately explains the response of the restart inhibit function for the chosen setting parameters.

References

[1] IEC60034-1 – Rotating electrical machines. Part 1: Rating and performance, Release 2004

[2] IEC62114 – Electrical insulation systems (ISM). Thermal classification, Release 2001

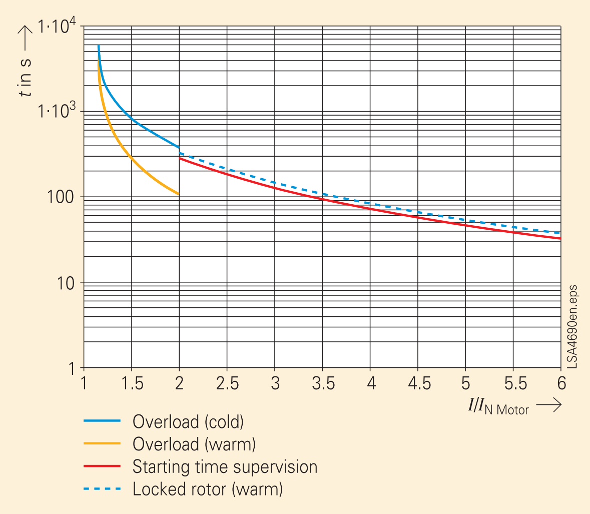


Fig. 8 Thermal characteristics according to the setting

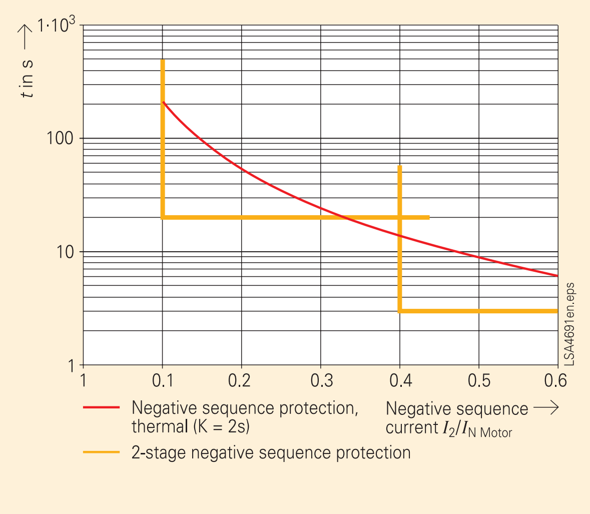


Fig. 9 Negative-sequence protection characteristics

Motor Protection: Requirements for Current Transformers

This chapter discusses the design of current transformers for motor protection applications. Various operating cases and typical protection principles are considered. Design is explained with reference to examples, based on a choice of two approaches, checking of existing current transformers and new design. These considerations are based, among other things, on the relevant IEC standards (IEC 60044-1, IEC 60044-6).

Formula symbols and definitions used

K_{ssc} =	factor of the symmetrical rated short-circuit current (example: transformer CI. 5P20 → $K_{ssc} = 20$)
K'_{ssc} =	effective factor of the asymmetrical short-circuit current
K_{td} =	transient rated dimensioning factor
I_{pn} =	primary rated transformer current
I_{sn} =	secondary rated transformer current
R_{ct} =	secondary winding resistance in Ω at 75 °C (or another specified temperature)
R_b =	rated resistive burden in Ω
R'_b =	$R_{lead} + R_{relay}$ = connected burden in Ω
R_{relay} =	relay burden in Ω
$R_{lead} = \frac{2 \cdot \rho \cdot l}{A}$	
where:	
l =	single conductor length between current transformer and device in m
ρ =	specific resistance = 0.0175 Ω mm^2/m (copper) at 20 °C (or another specified temperature)
A =	conductor cross-section mm^2
I_{start} =	motor starting current
$I_{start\ trans}$ =	transient starting current
k_{trans}	factor for the transient starting current

For current transformers defined via the symmetrical rated short-circuit current factor K_{ssc} and the rated resistive burden R_b (e.g.: 5P,10P), the effective factor of the symmetrical short-circuit current K'_{ssc} can be calculated in accordance with the following formula:

$$K'_{ssc} = K_{ssc} \cdot \frac{R_{ct} + R_b}{R_{ct} + R'_b}$$

Starting is crucial to stability when current flows through and with regard to the design of the transformers.

Requirements arising out of motor starting

The starting current I_{start} is in the range from four to seven times I_N with a DC time constant T_A of about 40 ms (<1 MW) to 70 ms (>1 MW). This is superimposed with a rush current of approximately the same order of magnitude which, however, decays in two to three cycles in accordance with a time constant T_{rush} of about 20 ms.

The starting current is therefore:

$$I_{start\ trans} = k_{trans} \cdot I_{start}\ ,\ \text{where } k_{trans} = 2 - 2.5$$

The minimum required factor of the symmetrical short-circuit current K'_{ssc} can be calculated in accordance with the following formula:

$$K'_{ssc} \geq K_{td} \cdot \frac{I_{start\ trans}}{I_{pn}}$$

the following condition must be met:
K'_{ssc} (required) ≤ K'_{ssc} (effective)

Example 1 Definite-time overcurrent-time protection, check of the existing current transformer

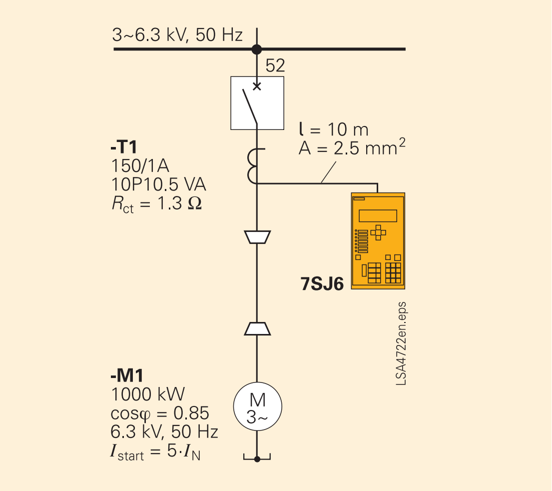


Fig. 1

$$I_N = \frac{P_N}{\sqrt{3} \cdot V_N \cdot \cos\varphi} = \frac{1000\ \text{kW}}{\sqrt{3} \cdot 6.3\ \text{kV} \cdot 0.85} = 107.8\ \text{A}$$

$$I_{start} = 5 \cdot I_N = 5 \cdot 107.8\ \text{A} = 537.5\ \text{A}$$

$$I_{start\ trans} = 2 \cdot I_{start} = 2 \cdot 537.5\ \text{A} = 1075\ \text{A}$$

Setting value $I>>$: $1.3 \cdot I_{start\ trans} = 1.3 \cdot 1075\ \text{A} = 1397\ \text{A}$

Note:
For $t>> = 0$ ms.
With a time setting of $t>> = 50$ ms, the setting value can be reduced.
(Refer to Chapter “Protection of medium-power motors”)

Requirement: $K'_{ssc} \geq \frac{I>>}{I_{pn}} = \frac{1397\ \text{A}}{150\ \text{A}} = 9.3$, but at least 20

The CT's rated burden in Ω amounts to:

$$R_b = \frac{S_n}{I_{sn}^2} = \frac{5\ \text{VA}}{1\ \text{A}^2} = 5\ \Omega$$

The actually connected burden (cable + device) amounts to:

$$R'_b = R_{lead} + R_{relay} = \frac{2 \cdot \rho \cdot l}{A} + 0.1\ \Omega = \frac{2 \cdot 0.0175\ \frac{\Omega\ \text{mm}^2}{\text{m}} \cdot 10\ \text{m}}{2.5\ \text{mm}^2} + 0.1\ \Omega = 0.24\ \Omega$$

This results in the effective factor:

$$K'_{ssc} = K_{ssc} \cdot \frac{R_{ct} + R_b}{R_{ct} + R'_b} = 10 \cdot \frac{1.3\ \Omega + 5\ \Omega}{1.3\ \Omega + 0.24\ \Omega} = 40.9$$

K'_{ssc} required = 20, K'_{ssc} effective = 40,9 → The dimensioning of the CT is correct.

Example 2 Differential protection, design and checking of a current transformer

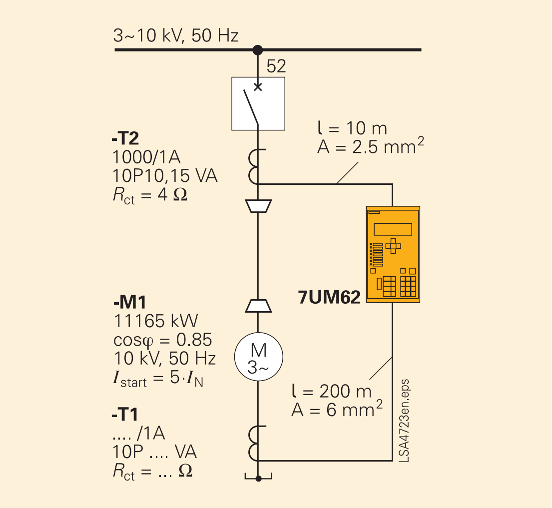


Fig. 2

2.1 Design of the current transformer – T1

$$I_N = \frac{P_N}{\sqrt{3} \cdot U_N \cdot \cos\varphi} = \frac{11165 \text{ kW}}{\sqrt{3} \cdot 10 \text{ kV} \cdot 0.85} = 758 \text{ A}$$

A CT with I_{pn}=1000 A is chosen.

$$I_{start} = 5 \cdot I_N = 5 \cdot 758 \text{ A} = 3790 \text{ A}$$

$$I_{start\ trans} = 2 \cdot I_{start} = 2 \cdot 3790 \text{ A} = 7580 \text{ A}$$

$$\text{Requirement: } K'_{ssc} \geq K_{td} \cdot \frac{I_{start\ trans}}{I_{pn}} = 5 \cdot \frac{7580 \text{ A}}{1000 \text{ A}} = 37.9$$

where $K_{td} = 5$ for the generator/motor differential protection (Catalog SIP 2006)

The CT's class should be 10P with 20 VA rated burden and an internal resistance $R_{ct} \leq 4\ \Omega$

The CT's rated burden in Ω is:

$$R_b = \frac{S_n}{I_{sn}^2} = \frac{20 \text{ VA}}{1 \text{ A}^2} = 20\ \Omega$$

The actually connected burden (cable + device) is:

$$R'_b = R_{lead} + R_{relay} = \frac{2 \cdot \rho \cdot l}{A} + 0.1\ \Omega = \frac{2 \cdot 0.0175 \frac{\Omega \text{ mm}^2}{\text{m}} \cdot 200 \text{ m}}{6 \text{ mm}^2} + 0.1\ \Omega = 1.266\ \Omega$$

This results in the rated factor:

$$K_{ssc} \geq \frac{R_{ct} + R'_b}{R_{ct} + R_b} \cdot K'_{ssc} = \frac{4\ \Omega + 1.226\ \Omega}{4\ \Omega + 20\ \Omega} \cdot 37.9 = 8.3$$

$K_{ssc} = 10$ is chosen

With this, all necessary CT data are available:

1000 A/1A, 10P10, 20 VA, $R_{ct} \leq 4\ \Omega$

2.2 Checking the existing transformer – T2

$K'_{ssc} = 37.9$ (from design of transformer – T1)

The CT's rated burden in Ω is:

$$R_b = \frac{S_n}{I_{sn}^2} = \frac{15\ \text{VA}}{1\ \text{A}^2} = 15\ \Omega$$

The actually connected burden (cable + device) is:

$$R'_b = R_{lead} + R_{relay} = \frac{2 \cdot \rho \cdot l}{A} + 0.1\ \Omega = \frac{2 \cdot 0.0175\ \dfrac{\Omega\ \text{mm}^2}{\text{m}} \cdot 10\ \text{m}}{2.5\ \text{mm}^2} + 0.1\ \Omega = 0.24\ \Omega$$

This results in the rated factor:

$$K'_{ssc} = K_{ssc} \cdot \frac{R_{ct} + R_b}{R_{ct} + R'_b} = 10 \cdot \frac{4\ \Omega + 15\ \Omega}{4\ \Omega + 0.24\ \Omega} = 44.8$$

K'_{ssc} required = 37.9, K'_{ssc} effective = 44.8 → The dimensioning of the CT is correct.

Note: Contrary to the star point CT (-T1), the required apparent power can be slightly lower because the distance from the protection is clearly shorter. If the final distance is not clear, the worst case must be reckoned with and identical current transformers must be provided.

Example 3 Differential protection with bushing-type transformers

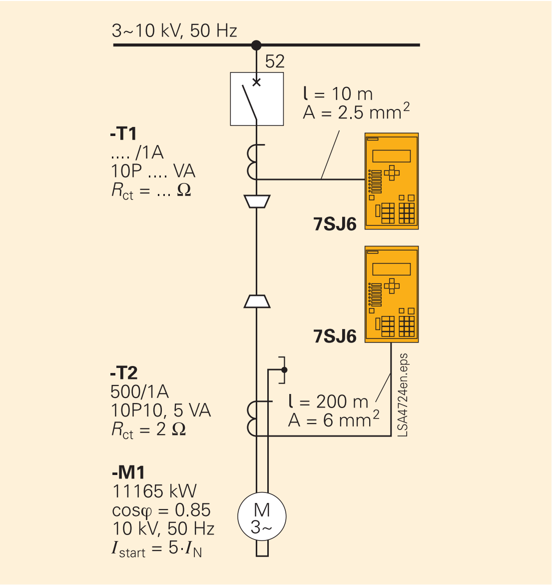


Fig. 3

3.1 Current transformer – T1

The classic motor protection functions (overload, starting supervision, negative-sequence (unbalanced-load), etc. operate with this current transformer).

$$I_N = \frac{P_N}{\sqrt{3} \cdot V_N \cdot \cos\varphi} = \frac{11165\ \text{kW}}{\sqrt{3} \cdot 10\ \text{kV} \cdot 0.85} = 758\ \text{A}$$

A CT with I_{pn} = 1000 A is chosen.

$I_{start} = 5 \cdot I_N = 5 \cdot 758\ \text{A} = 3790\ \text{A}$

$I_{start\ trans} = 2 \cdot I_{start} = 2 \cdot 3790\ \text{A} = 7580\ \text{A}$

Setting value $I >> : 1.3 \cdot I_{start\ trans} = 1.3 \cdot 7580\ \text{A} = 9854\ \text{A}$

Note:
For $t >>$ = 0 ms.
With a time setting of $t >>$ = 50 ms, the setting value can be reduced.
(Refer to Chapter “Protection of medium-power motors”)

Requirement: $K'_{ssc} \geq \frac{I >>}{I_{pn}} = \frac{9854\ \text{A}}{1000\ \text{A}} = 9.85$, but at least 20

The CT's class should be 10P with 5 VA rated burden and an internal resistance $R_{ct} \leq 4\ \Omega$.
The CT's rated burden in Ω amounts to:

$$R_b = \frac{S_n}{I_{sn}^2} = \frac{5\ \text{VA}}{1\ \text{A}^2} = 5\ \Omega$$

The actually connected burden (cable + device) amounts to:

$$R'_b = R_{lead} + R_{relay} = \frac{2 \cdot \rho \cdot l}{A} + 0.1\ \Omega = \frac{2 \cdot 0.0175 \frac{\Omega\ \text{mm}^2}{\text{m}} \cdot 10\ \text{m}}{2.5\ \text{mm}^2} + 0.1\ \Omega = 0.24\ \Omega$$

This results in the rated factor:

$$K_{ssc} \geq \frac{R_{ct} + R'_b}{R_{ct} + R_b} \cdot K'_{ssc} = \frac{4\ \Omega + 0.24\ \Omega}{4\ \Omega + 5\ \Omega} \cdot 20 = 9.42$$

K_{ssc} = 10 is chosen

With this, all necessary CT data are available:

1000 A/1 A, 10P10, 20 VA, $R_{ct} \leq 4\ \Omega$

3.2 Bushing-type transformer – T2

For machines connected via cables, reliable differential protection with high response sensitivity can be realized with this method. The prerequisite is that the three phases are returned separated from the star point side and are routed through the bushing-type transformer in the opposite direction. If the machine winding is fault-free, the currents in the transformer cancel each other out and no current flows into the (differential) current relay. The current comparison is highly precise without saturation problems, taking place as a magnetic (self-balancing) operation.
No stabilization is necessary, i.e. simple current relays can be used. The pickup value can be adjusted to 2 to 5 % of the machine’s rated current.
One 7UM62 can also be used instead of two 7SJ6 units, in which case the overcurrent function must be assigned to the bushing-type transformer.

CT requirement for **-T2**
The (differential) current relay must respond to high-current internal faults.

As the setting value is very low and the total current is zero during fault-free operation, a CT with 500 A/1 A, 10P10, 5 VA, $R_{ct} = 2\,\Omega$ is chosen, with the requirement: $K'_{ssc} \geq 20$ (analogous to the definite-time overcurrent-time protection)

The CT's rated burden in Ω is:

$$R_b = \frac{S_n}{I_{sn}^2} = \frac{5\ \text{VA}}{1\ \text{A}^2} = 5\ \Omega$$

The actually connected burden (cable + device) is:

$$R'_b = R_{lead} + R_{relay} = \frac{2 \cdot \rho \cdot l}{A} + 0.1\ \Omega = \frac{2 \cdot 0.0175\ \frac{\Omega\ \text{mm}^2}{\text{m}} \cdot 200\ \text{m}}{6\ \text{mm}^2} + 0.1\ \Omega = 1.266\ \Omega$$

This results in the rated factor:

$$K'_{ssc} = K_{ssc} \cdot \frac{R_{ct} + R_b}{R_{ct} + R'_b} = 10 \cdot \frac{2\ \Omega + 5\ \Omega}{2\ \Omega + 1.226\ \Omega} = 21.4$$

K'_{ssc} required = 20, K'_{ssc} effective = 21.4 → The dimensioning of the CT is correct.

Summary

The requirements for current transformers are defined not only by the starting operation, but also by the requirements of the protection principle. Further important defining variables are the burden through the feeder and also the current transformer’s internal burden. The current transformer types chosen in the examples can certainly be used for orientation. However, a general check is nevertheless recommended.

Protection of Low-Power Motors

Principles and settings for the protection of a small (asynchronous) motor are discussed below. Particular attention is devoted to design of the earth-fault protection for earthed, isolated and resonant-earthed power systems, representative of all kinds and sizes of motors. The 7SJ600 or the 7SJ602 is considered a preferred protective relay for small motors.

■ 1. Protection functions

Protection functions	Abbreviations	ANSI
Time-overcurrent relay, phase	$I>>, I>, I_p$	50, 51
Non-directional/directional earth-fault protection *, **	$I_{EE\ dir.}>>, I_{EEdir.}>, V_E>$	51N, 51Ns, 67Ns, 59N
Displacement voltage protection		59N
Thermal overload protection	$I^2 t >$	49
Starting time supervision	$I_{start}{}^2\ t$	48
Restart inhibit	$I^2 t$	66, 49R
Negative-sequence (unbalanced-load) protection	$I_2 >, t = f(I_2)$	46
Temperature monitoring **	ϑ (Thermobox)	38

* *Required depending on star point connection and system topology*

** *With 7SJ602 only*

The following protection functions are available:

7SJ600:

Time-overcurrent protection phase/earth, thermal overload protection, starting time supervision, restart inhibit and negative-sequence (unbalanced-load) protection

7SJ602 (from V3.5) additionally:

Sensitive earth-fault protection
Directional earth-fault protection for isolated and compensated systems
Time-undercurrent protection
Temperature monitoring by RTD-box

Besides the SIPROTEC relays 7SJ600 and 7SJ602 presented here, it goes without saying that the 7SJ61,62,63,64 relays in the SIPROTEC 4 family with a wider scope of functions are also suitable. Refer to the chapters on protection of medium- and high-power motors.

Connection of the 7SJ602 for an isolated or resonant-earth system with earth-fault direction detection.

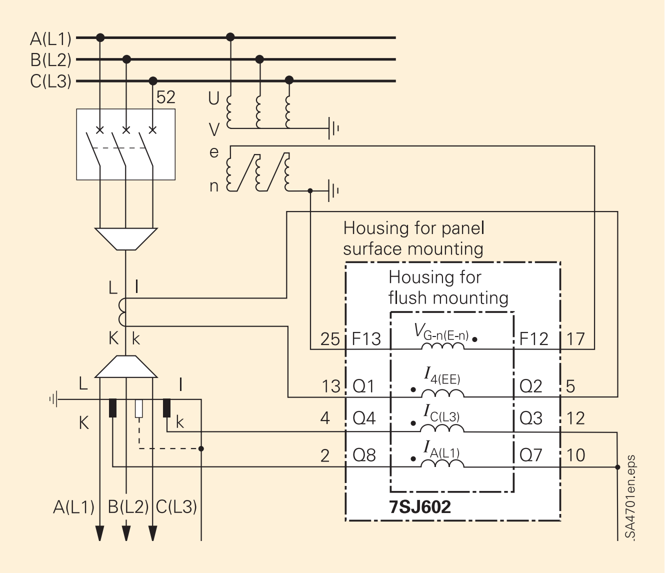


Fig. 1 Connection with 3 current inputs $I_{A(L1)}$-$I_{B(L2)}$-$I_{4(EE)}$ for sensitive earth-fault protection and displacement voltage input $V_{e\text{-}n}$

2. Available motor data

Size	Value
Power	460 kW
Rated voltage	6 kV
Rated motor current	48 A
Max. starting current (at 100 % V_N)	312 A = 6.5 · $I_{N, M}$
Starting time (at 100 % V_N)	2.1 sec
Heating time constant	40 min
Cooling time constant at standstill	240 min
Max. continuous thermal rating current	58 A = 1.2 · $I_{N, M}$
Max. locked rotor time	18 sec at 6.5 · $I_{N, M}$

A 75 A/1 A current transformer is chosen for the phases and a core-balance current transformer 60 A/1 A, as well as 6 kV/100 V voltage transformers.

3. General power system data

The current and voltage transformer data and the type of connection are entered in the unit under “1100 Power System Data”.

Here are the DIGSI parameters of a 7SJ602:

No.	Parameter	Value
1100	POWER SYSTEM DATA	
1101	Rated system frequency	fN 50 Hz
1105	Primary rated current	75 A
1106	Secondary rated current	1 A
1111	Matching factor Iee/Iph for earth current	0.800
1112	CT nom. current IEEp, sec	1 A
1113	Nominal VT voltage, primary	6.00 kV
1114	Nominal VT voltage, secondary	100 V
1115	Reverse power direction	off
1116	Threshold circuit breaker closed	0.10 I/In
1118	Nominal current of motor in relation to Tr.C.	0.6
1119	Startup current in relation to nominal current	6.5
1120	Maximum startup time	8.0 s
1121	Reset thermal image on startup	yes
1134	Minimum trip command duration	0.15 s
1135	Maximum close command duration	1.00 s

1118: Via this setting, the entries for the “starting time supervision” and “restart inhibit” motor protection functions are referred to rated motor current. 1119: Motor starting or locked-rotor current. 1120:Tthe rotor locking time for 6.5 $I_{N,M}$ is 18 s, and the startup time for the 422 kW pump used in the example is 2.1 s. An interme- diate value of 8 s was chosen (see also comments on starting time supervision).

4. Protection functions

4.1 Time-overcurrent protection, phase

No.	Parameter	Value
1300	O/C PROTECTION PHASE FAULTS	
1301	O/C protection for phase faults	on
1302	Duration of temporary pickup value c/o	10.00 s
1303	Pickup value of the high-set inst. stage I>>>	1.2 I/In
1304	Pickup val. of high-set inst. stage I>>> (dyn)	6.3 I/In
1305	Pickup value of the high-set stage I>>	1.2 I/In
1306	Pickup value of the high-set stage I>> (dyn)	6.3 I/In
1307	Trip time delay of the high-set stage I>>	0.05 s
1308	Pickup value of the overcurrent stage I>	1.2 I/In
1309	Pickup value of the O/C stage I> (dyn)	1.2 I/In
1310	Trip time delay of the overcurrent stage I>	10.00 s
1311	Measurement repetition	no
1319	Manual close	I>> undelayed

Dynamic thresholds are used, i.e. during the increased current in motor starting, the overcurrent stages *I*>>> (1303) and *I*>> (1305) are raised appropriately (1304: *I*>>> dyn, 1306: *I*>> dyn) and are lowered again after starting (hold time 1302: 10s). Advantage: a sensitive setting with a short tripping time is possible during normal operation. As an additional reserve stage, stage *I*> is operated with a tripping time (1310) longer than the starting time.
All stages are set to 1.5 times the maximum operating current, e.g. *I*>>, dyn = 1.5 · 6.5 · 0.64 = 6.24;
6.5: max. starting current,
0.64: motor/transformer rated current conversion.
I>> = 1.5 · 1.2 · 0.64 = 1.15.
1.2: max. continuous thermal current,
0.64: motor/transformer rated current conversion.

4.2 Negative-sequence protection

No data is available from the motor manufacturer, and so the following settings can be used as recommended values:

No.	Parameter	Value
1500	UNBALANCED LOAD PROTECTION	
1501	State of the unbalanced-load protection	on
1502	Pickup value of neg. seq. I low-set stage I2>	8 %
1503	Trip delay of neg. seq. I low-set stage TI2>	20.00 s
1504	Pickup value for high current stage	26 %
1505	Trip time delay for high current stage	3.00 s

The values refer to the rated transformer current. 1502 and 1504 are set to approx. 10 % or 40 % of the rated motor current. Further information can be found in the chapter entitled “Thermal stress of motors and necessary protection functions”.

4.3 Thermal overload protection

Thermal overload protection serves to protect the stator against inadmissible temperature rise.

No.	Parameter	Value
2700	THERMAL OVERLOAD PROTECTION	
2701	State of thermal overload protection	on
2702	K-factor for thermal overload protection	0.77
2703	Time constant for thermal overload protection	60.0 min
2704	Multiplier of time constant at standstill	4.00
2705	Thermal warning stage	90 %

All values are referred to rated transformer current.
2702: The figure can be obtained from the motor’s thermal withstand curve and is the asymptotic value of the characteristic at the bottom.
In the example,

$$k = 1.2 \cdot \frac{I}{I_{N,\,M}}$$

Referred to rated transformer current:

$$k = 1.2 \cdot \frac{I_{N,\,M}}{I_{N,\,CT}} = 1.2 \cdot 0.64 = 0.77$$

2703 and 2704 are taken from the data sheet; important: the thermal time constant during continuous operation and not the copper time constant for short-time operation must be used for 2703.
2705: The thermal warning stage picks up when the calculated temperature reaches 90 % of the max. permissible temperature.

4.4 Starting time supervision

This serves to protect the rotor during motor starting. It is advisable to permit a maximum starting time that lies between the real starting time (2.1 s) and the maximum locked-rotor time (18 s), on the one hand to avoid responding too sensitively in the event of long starting times, and thus deactivating the motor unnecessarily, on the other hand, though, to also avoid reaching the rotor insulation's absolute thermal limit. In the case of the 7SJ602, both values are located in the system data parameter block, where they are described.

No.	Parameter	Value
2800	STARTING-TIME SUPERVISION	
2801	Supervision of starting time	on
2803	Base value Istrt of permissible start-up curr.	1.6 I/In
2804	Block of the I>/Ip stages during start-up	no

2803: If the measured phase current rises above this value, motor starting is detected and the function is activated. A reasonable value for starting detection is 2.5 times the rated motor current $I_A = 2.5 \cdot 0.64 = 1.6$. 2804 offers the possibility of blocking the overcurrent stages to avoid overcurrent tripping during motor starting.

Our example, however, uses dynamic threshold boosting during starting and a reserve stage $I>$ with a tripping time longer than motor starting, and so this must not be blocked.

4.5 Restart inhibit

This function prevents excessively frequent starting of the motor in succession. As starting time supervision does not have a thermal memory, it would permit several starts in direct succession provided the maximum start-up time were not exceeded. Generally, though, motor manufacturers permit only three starts from the cold operating state (4503 + 4504) and two from the warm state (4503).

No.	Parameter	Value
4500	MOTOR START PROTECTION	
4501	Motor start protection	on
4502	Temperature equalization time	1.0 min
4503	Maximum permissible number of warm-starts	2
4504	Difference between no. of cold and warm-starts	1
4505	Factor for tau during standstill	5.0
4506	Factor for tau during operation	2.0
4507	Minimum blocking time for motor protection	6.0 min

Calculation is based on a thermal homogeneous-body model similar to the standard overload protection that operates for the stator winding. The time constant during operation is equal to the value set in 2703, and an additional value 4505 can be set for prolongation during motor standstill. 4502 is an empirically based value and can generally be left set as it is. If the manufacturer specifies a minimum inhibit time between two starts, this can be set in 4507. It acts in addition to the blockage derived dynamically from the thermal image. Here, the k factor, which must be worked out in the case of overload protection, is determined automatically on the basis of the number of starts for cold and warm and is normally considerably lower for the rotor than for the stator.

4.6 Undercurrent monitoring

Undercurrent monitoring serves to protect the driven load and detects a load loss that might cause damage, e.g. pumps running dry.

The settings depend on the type and size of the driven load.

No.	Parameter	Value
4600	UNDERCURRENT MONITORING	
4601	Limit for undercurrent monitoring	0.20 I/In
4602	Delay time for undercurrent monitoring	10.0 s
4603	Undercurrent monitoring	on

4.7 Breaker-failure protection

This serves to repeat (on another command relay) a TRIP command that does not lead to opening of the circuit-breaker, thus tripping any second release coil of the circuit-breaker or a higher-level circuit breaker.

No.	Parameter	Value
3600	BREAKER-FAILURE PROTECTION	
3601	Circuit breaker failure protection	on
3602	Delay time T-B/F	0.3 s
3603	Analysis of auxiliary contacts for B/F	off

The delay time must be greater than the circuit-breaker's run time and the reset time of the BFP including safety reserve.

4.8 Displacement voltage protection V_E>

No.	Parameter	Value
3300	DISPLACEMENT VOLTAGE PROTECTION VE>	
3309	Displacement voltage level	0.10 U/Un
3311	Delay time for annunciation of VE>	1.00 s
3312	Delay time T-VE of the VE> stage	10.00 s

This function serves to detect an earth fault in isolated and compensated power systems and is used in addition to overcurrent sensitive earth-fault protection. Especially at the infeed of a busbar, single-pole faults cannot be detected due to the zero sequence current and are indicated by the V_E protection. The fault location can be determined by switching operations and the fault can be cleared.

Below, earth-fault protection is described in detail, representative for all kinds and sizes of motors.

4.9 Earth-fault protection

Earth-fault protection mainly depends on the power system's star point earthing. An earth fault occurs in isolated and compensated power systems (Petersen coil at the system's star point); i.e. the occurring fault currents are relatively low and therefore do not need to be deactivated in the shortest of times. Power system operators can continue operation of their networks for a limited time and eliminate the fault through switching operations. By contrast, in impedance or solidly earthed power systems, the fault current is so high that is has to be switched off straight away.

a) Solid or low-impedance star point earthing

The fault currents are short-circuit currents and must be eliminated fast. Any resistance installed at the star point serves to limit the earth-fault currents in the event of earth faults (ph-e, ph-ph-e) to a certain maximum value.

- Selectivity criteria
  The short-circuit currents occur only in the feeder containing the fault. Short-circuit currents can be detected that are lower than the motor's rated current because this is approximately symmetrical during normal operation; i.e. it does not contain a negative-sequence and zero-sequence component. The setting sensitivity limit is defined by asymmetries and measuring errors of the current transformers – especially in a Holmgreen circuit – and asymmetries of operation. It is therefore recommended not to set more sensitively than 0.1 – 0.2 $I_{N,\,CT}$.

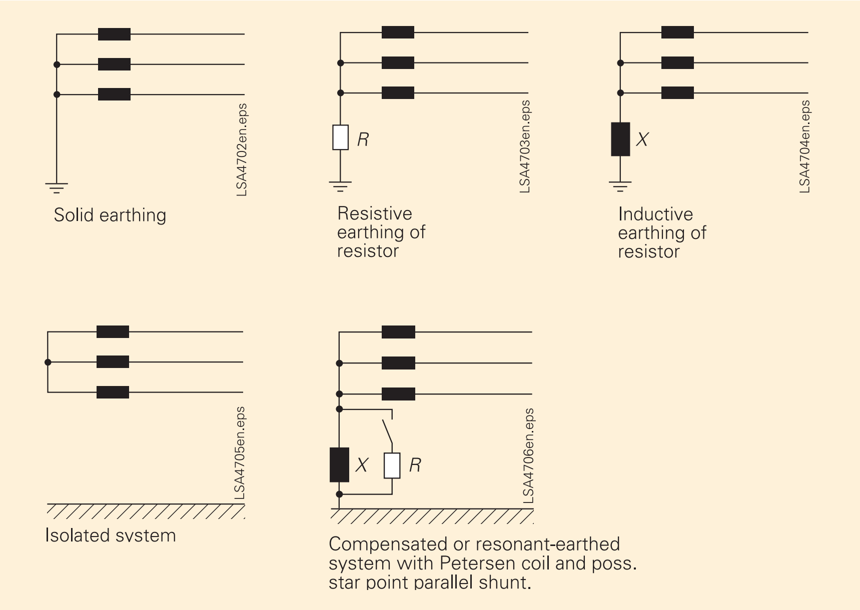


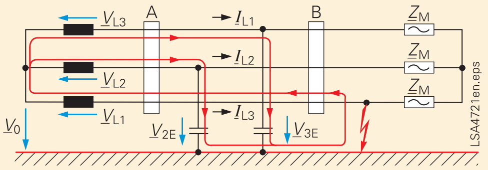
Fig. 2 shows an overview of the usual star point earthing configurations (solid and inductive earthing, however, is uncommon for motor protection applications).

No.	Parameter	Value
1400	O/C PROTECTION EARTH FAULTS	
1401	O/C protection for earth faults	on
1402	Pickup value of the high-set stage IE>>	0.20 I/In
1403	Pickup value of high-set E/F stage IE>> (dyn)	1.00 I/In
1404	Trip time delay of the high-set stage IE>>	0.05 s
1405	Pickup value of the overcurrent stage IE>	+ * I/In
1406	Pickup value of def. time E/F stage IE> (dyn)	+ * I/In
1407	Trip time delay of the overcurrent stage IE>	60.00 s
1408	Measurement repetition	no
1416	Manual close	IE>> undelayed

- 1402: Earth-fault protection pickup value.
  1403: Due to the higher operating currents during starting, the pickup threshold is also proportionally pulled up because of the measuring errors.
  1404: Fast tripping is possible as no grading times have to be considered.

b) Isolated power systems

The earth-fault current is generated by the line-earth capacitances (Fig. 3).



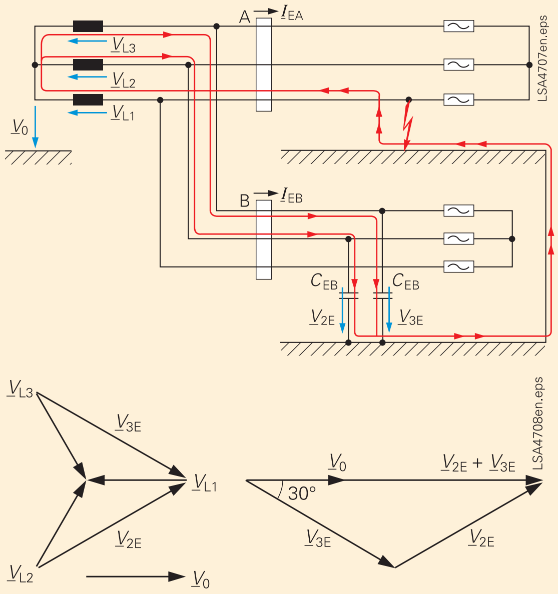
All currents cancel each other out (sum total is 0), when the zero current $\underline{I}_o = \frac{1}{3}(\underline{I}_{L1} + \underline{I}_{L2} + \underline{I}_{L3})$ is measured in point A.

In point B, however, only the fault currents of the faulty phase can be seen.

Fig. 3 Earth fault in an isolated system, fault currents

Currents generated by line capacitances that lie downstream in the direction of the fault cancel each other out with the current returning in the faulty phase (measurement point A). By contrast, capacitive currents behind the measurement point are detected by it via the fault phase (measurement point B). Applied to several feeders in an isolated system, this means that the capacitive currents of the healthy phases including the infeed are measured in the faulty phase.
The amount of the fault current that is measured on the faulty feeder is therefore equal to the sum of the capacitive currents of the remaining, galvanically coherent healthy power system. Each healthy feeder carries a part of the fault current, which is also measured by the protection relays installed there (Fig. 4).

Earth fault in an isolated system



$$\underline{I}_{E,B} = j\omega C_{E,B}(\underline{V}_{2E} + \underline{V}_{3E});\ \underline{V}_{2E} = V_{2E}\, e^{j\ 30°};\ \underline{V}_{3E} = V_{3E}{}^{-j\ 30°}$$

$$\underline{V}_{2E} = V_{2E}(\cos 30° + j \sin 30°);\ \underline{V}_{3E} = V_{3E}(\cos 30° - j \sin 30°)$$

$$|\underline{V}_{2E}| = |\underline{V}_{3E}| = V_N$$

$$\rightarrow \underline{V}_{2E} + \underline{V}_{3E} = V_N \cdot 2 \cdot \cos 30° = 2 \cdot \frac{\sqrt{3}}{2} \cdot V_N = \sqrt{3}\, V_N$$

$$\boxed{\underline{I}_{E,B} = j\omega C_{E,B} \cdot \sqrt{3} \cdot \underline{V}_N} \quad \boxed{\underline{I}_{E,A} = -\underline{I}_{E,B} = -j\omega C_{E,B} \cdot \sqrt{3} \cdot \underline{V}_N}$$

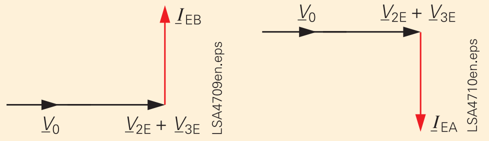


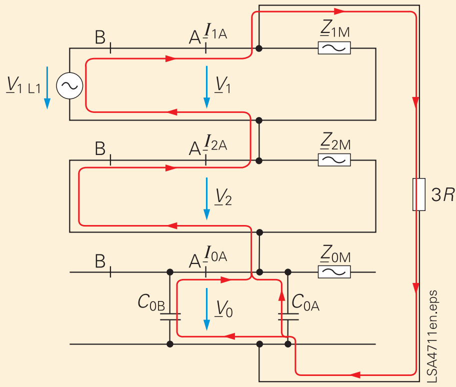
Fig. 4 Earth fault in an isolated system, amount and phase angle of I_{EA}, I_{EB} and V_0

In this case with a fault on feeder A, the zero sequence current

$\left(\frac{1}{3} I_{EA}\right)$ (measured in point A) lags behind the zero-sequence voltage by 90°; current I_{EB} (measured in point B) leads by 90°.
The zero sequence current is determined by the total capacitance (not shown in the diagram) of line B and possible further lines.

Remark: The direction of the earth currents I_E of the SIPROTEC relays is opposite to the zero-sequence currents. So the directional characterisitics in the manual differ from the above drawing in this respect.

Earth-fault in isolated system, component equivalent circuit diagram for fault on feeder A



$\underline{V}_{1,L1}$: Component of positive-sequence system of phase L1 (= V_1)

$\underline{V}_2$, $\underline{V}_o$: Negative-sequence system and zero-sequence system's voltage

R_F: Fault resistance

$C_{o,B}$: Zero-sequence system capacity of feeder B

$\underline{Z}_{1M}$, $\underline{Z}_{2M}$, $\underline{Z}_{0M}$: Positive, negative, zero sequence of motor

If the transfer resistance of the fault is neglected, it can be seen, that $V_2 = 0$; $V_0 = -1$ and that the fault current is determined by capacity $C_{0B} >> C_{0A}$ and voltage V_1.

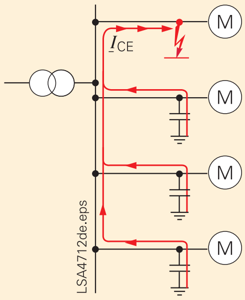
$$\underline{I}_{0A} = \underline{I}_{1A} = \underline{I}_{2A} = \frac{\underline{V}_1}{3R_F + \underline{Z}_{C0B}} \text{; where } R_F = 0$$

$$\rightarrow \underline{I}_{0A} = \frac{\underline{V}_1}{\underline{Z}_{C0B}} = \frac{\underline{V}_1}{\frac{1}{j\omega C_{0B}}} = V_1 \cdot j\omega C_{0B} = -j\omega C_{0B} \cdot \underline{V}_0$$

$$\underline{I}_{0A} = -j\omega C_{0B} \cdot \underline{V}_0 = \frac{1}{3} \underline{I}_{EA}$$

Fig. 5 Component equivalent circuit diagram in the case of a single-pole fault. It can clearly be seen, that the fault current is mainly limited by the phase- earth capacitance of the remaining system. When compared to Fig. 3, it can be seen, that the direction as well as the amount of the fault current correspond with the representation with natural quantities.

- Selectivity criteria
  In contrast to the earthed system, a current is measured in each fault-free feeder whose amount is proportional to the phase-earth capacitance in the forward direction. The distribution of the capacitances determines whether an overcurrent criterion alone is sufficient for feeder-specific selectivity. Therefore, for each feeder the current in the event of an earth fault on this feeder (forward direction) must be higher than the current in the event of an earth fault in reverse direction. This is the case, when for each feeder of the galvanic connected power system the capacity of the remaining system (system without the faulted feeder) is much higher than the capacity of the faulted feeder. The current for an earth fault in forward direction depends on the capacity of the remaining power system while the current for an earth fault in reverse direction depends on the capacity of the feeder.



Selectivity by current criterion

The fault current in the faulty feeder is clearly higher for each feeder than for the fault current in the healthy feeders.

Fig. 6 Selectivity by current criterion, principle

Another requirement of the earth-fault protection is the detection of earth-faults within the motor. Generally, a coverage amounting to 80-90 % of the stator winding is demanded.

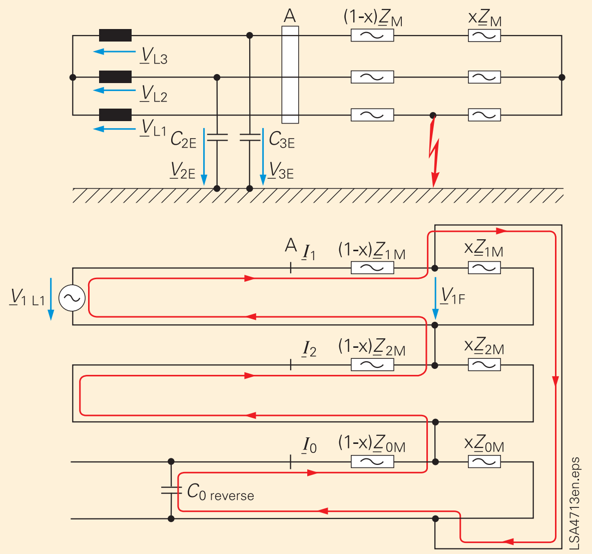


Fig. 7 Isolated system, earth fault in the stator of the motor

The voltage driving the zero current $\underline{I}_0$ is the voltage at the fault location $\underline{V}_{1,F}$. It arises due to a voltage divider

$$\frac{x\underline{Z}_{1M}}{\underline{Z}_{1M}} \text{ i.e. } \underline{V}_{1F} = -\underline{V}_0 = x \cdot \underline{V}_1$$

If we neglect the resistances along the path of the current $\underline{I}_0$ ((1-x)$\underline{Z}_{0M}$, (1-x)$\underline{Z}_{2M}$), and the reactances of the feeding cable, which results in a very good approximation in view of the relatively high resistance of the zero capacitance in comparison with it, then $\underline{I}_0$ (x) is proportional to x.

$$\underline{I}_0(x) = x \cdot \frac{\underline{V}_N}{\sqrt{3}} \cdot \omega \cdot C_{0\text{ rev}}$$

Therefore, in the case of fault coverage amounting to 90 % of the stator winding, the resulting zero-sequence current is only 10 % of the zero-sequence current that arises in the event of a fault on the supply line, i.e. outside the stator.

■ *1st example:* *Selectivity through overcurrent*

A power system is assumed with ten motors, each of them connected by means of a cable measuring 200 m in length to a busbar that is fed by a transformer:

Transformer: $V_N = \dfrac{20\text{ kV}}{6\text{ kV}}$; $S_N = 6$ MVA, $u_k = 0.08$

The cables have a length-related capacitance to earth $C_E = 0.257$ µF / km.
The motors have a stator-earth capacitance of 0.12 µF
As our motors have a rated current of 48 A, the next largest phase current transformers of the preferred type with 75 A/1 A are chosen.

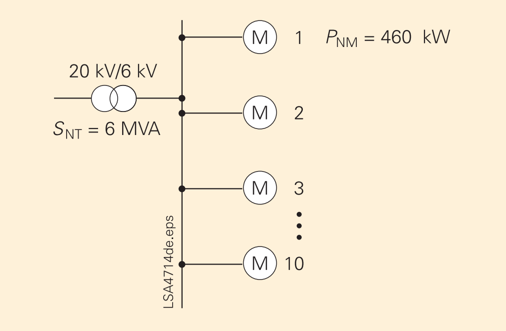


Fig. 8 Example system with 10 identical motors

The earth-fault protection of each feeder should not only reliably find faults on the supplying cable, but also faults in the motor up to a range of at least 80 % of the stator winding (calculated from the outside).

1. Calculation of a feeder's total capacitance:

$$C_{0,\text{ tot}} = 0.2\text{ km} \cdot 0.257\,\frac{\mu\text{F}}{\text{km}} + 0.12\,\mu\text{F} = 0.1714\,\mu\text{F}$$

2. Zero-sequence current of a feeder in the event of a fault in the reverse direction outside the motor:

$$I_{0,\text{rev}} = \omega \cdot C_{0,\text{tot}} \cdot \frac{U_N}{\sqrt{3}} = 100\,\frac{\pi}{\text{s}} \cdot 0.1714 \cdot \frac{10^{-6}\text{s}}{\Omega} \cdot \frac{6\text{ kV}}{\sqrt{3}}$$
$$I_{0,\text{rev}} = 0.187\text{ A (primary)}$$
$$I_{E,\text{rev}} = 3 \cdot I_{0,\text{rev}} = 0.561\text{ A (primary)}$$

Each feeder protection relay detects this fault current in the event of a fault in the reverse direction. Under no circumstances may it pick up, i.e. the current threshold should be approximately 50 % above this value, also due to the transient condition on occurrence of the earth fault.

$I_{EE}> = 3 \cdot 1.5 \cdot I_{0,\text{ rev}} = 0.84$ A (primary).

With these very low primary currents, preference must be given here to a core-balance CT over a Holmgreen circuit. To measure an adequately high current on the secondary side, preference is given to a transformation ratio of 60 A/1 A over a higher ratio such as 100 A/1 A. With a tranformation ratio of 60/1, we get a setting of $I_{EE}> = 14$ mA.

The following current is measured in the event of a fault in the forward direction (factor x of the stator winding):

$\underline{I}_{0,\text{fwd}} = 9 \cdot \underline{I}_{0,\text{rev}} \cdot x$, because the nine healthy feeders now supply the fault current.

$I_{0,\text{fwd}} = 9 \cdot 0.187\text{ A} \cdot 0.2 = 0.337\text{ A}$

$I_{E,\text{fwd}} = 3 \cdot I_{0,\text{fwd}} = 1\text{ A}$

This value is approximately 20 % higher than the $I_{EE}>$ primary setting of 0.84 A. This therefore ensures a range of 80 % into the motor.

No.	Parameter	Value
7800	SCOPE OF FUNCTIONS	
7801	Characteristic of O/C protection	Definite time
7802	Temporary pickup value change over (O/C-st.)	Existent
7803	Unbalanced-load protection	Existent
7804	Thermal overload protection	With memory
7805	Supervision of starting time	Existent
7806	Direction determination for sensitive earth	Existent
7807	Characteristics for O/C earth	Definite time
7835	Breaker fail protection	Existent
7839	Trip circuit supervision	Bypass resistor, 1 BI
7840	Undercurrent monitoring	Existent
7841	Motor start protection	Existent

7806: Direction determination can be deactivated in this example.

Nro.	Parameter	Value
3000	EARTH FAULT IN COMPENSATED/ ISOLATED NETWORKS	
3001	High-sensitivity earth-fault protection	on
3013	IEE>> stage of high-sensitivity E/F prot.	0.014 I/In
3014	Delay time T-IEE>> of the IEE>> stage	0.50 s
3015	IEE> stage of high-sensitivity E/F prot.	+* I/In
3016	Pickup value of high-set stage IEE>> (dyn)	+* I/In
3017	Pickup value of O/C stage IEE> (dyn)	+* I/In
3018	Delay time T-IEE> of the IEE> stage	5.00 s
3019	Measurement repetition for E/F pickup	no
3028	Manual close	IE>> undelayed

3001: Sensitive earth-fault protection is activated.
3013: 14 mA ensures that the non-directional stage I_{EE}>> will not pickup in the event of reverse faults.
3014: To prevent pickup or tripping due to transients, e.g. on starting of the motor, the delay time is increased to at least 0.5 s. In particular, a long delay time is recommended for a Holmgreen circuit because, in this case, transformer asymmetries simulate a zero-sequence current on the secondary side that does not exist on the primary side.

Other similar power system configurations where the earth-fault current suffices as the selectivity criterion may be:

- Motors and several transformers for low voltage in the same power system with approximately identical cable length.
- Infeed without a transformer at the transfer point so that the entire capacitance of the previous power system feeds to faults in the motor feeders. Depending on the size of the previous power system, considerably higher fault currents can arise here that are also mastered with a Holmgreen circuit. The secondary settings should not be below approximately 0.3-0.5 I/I_N.

Faults on the busbar, however, are not detected by the protection relay at the infeed and they must be signalled with the aid of a voltage relay or the V_0 protection function of the 7SJ602.

2nd example: Selectivity through directional earth-fault protection

The power system above consists of only two motors because the other motors are now no longer on the system.
In this case, the current in each feeder is the same for internal and external faults. Therefore, the current as the sole criterion does not suffice for selective tripping. In addition to the zero current, the fault direction must be determined by way of the zero voltage.

In Fig. 4, we see that the angle of the zero current and voltage deviates by 180° between the forward and reverse directions. This is a reliable and relatively robust directional criterion. This is also why no special accuracy demands are placed on the transformers in the isolated system either.
A Holmgreen circuit of the current transformers frequently suffices for measurement of the earth current. The statements above in relation to measuring accuracy apply.

As the fault currents are now very low ($I_{0,\,\min} = 0.187 \cdot 0.2\ \text{A} = 0.0374\ \text{A}$ primary), they can no longer be measured with the transformers commonly used (e.g. core-balance current transformers 60 A/1 A or phase current transformers 75 A/1 A). A common solution to this problem is to use an earthing transformer at the busbar that increases the zero-sequence current in the isolated power system.

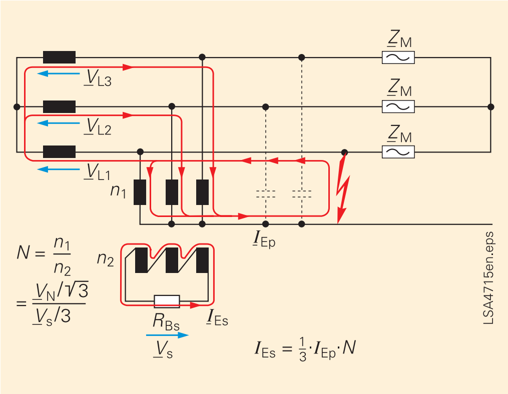


Fig. 9 Increasing the earth current by an earthing transformer

Fig. 9 shows connection of an earthing transformer in a Yd circuit. A load resistor is connected to the open delta winding and allows a current to flow through all secondary windings. On the primary side, a zero-sequence current arises in each phase, i.e. also in the faulty phase, although there is no driving voltage on the primary side here. This zero-sequence current flows into the fault location via the earthing transformer's star point and closes itself through the respective cables via the feeding transformer's star point. The dimensioning of the load resistor must be such that the lowest zero-sequence current to be measured, i.e. in the event of a fault in the motor, e.g. in the case of 20 % of the stator winding, can still be measured with the associated feeder protection.

Generally, secondary settings below 5-10 mA should be avoided (measuring tolerances of the core-balance current transformers and digital resolution of the protection).

3rd example Increase of the earth current by using an earthing transformer

The zero-sequence current of the second example should be increased so that an earth current of at least 10 mA secondary can be measured in the event of a fault on 90 % of the stator winding.

An earthing transformer with 500 V secondary and a core-balance CT 60 A/1 A are used.
Calculation of the load resistance:
With the above-mentioned data, the corresponding minimum primary zero-sequence current is:

$$I_{0\min} = \frac{1}{3} \cdot 60 \cdot 10\ \text{mA} = 200\ \text{mA}$$

$$I_{E\min} = 3 \cdot I_{0\min} = 600\ \text{mA}$$

In the event of a fault outside the stator, the fault current is

$$I_{Ep} = \frac{1}{x} \cdot I_{E\min} = 6\ \text{A}$$

$$I_{Es} = \frac{1}{3} \cdot TR_{ET} \cdot I_{Ep} = \frac{1}{3} \cdot \left(\frac{6\ \text{kV} / \sqrt{3}}{500\ \text{V} / 3} \right) \cdot 6\ \text{A} = 41.57\ \text{A}$$

$$R_{Bs} = \frac{V_s}{I_{ES}} = \frac{500\ \text{V}}{41.57\ \text{A}} = 12\ \Omega$$

Power dimensioning:

At the full displacement voltage R_{Bs} consumes a power of

$$P = \frac{V_s^{\,2}}{R_{Bs}} = 0.25 \cdot \frac{10^6\ \text{V}^2\text{A}}{12\ \text{V}} = 20.8\ \text{kW}$$

The load resistor and earthing transformer must be designed for this power.

As earthing transformers including load resistor are loaded only during a fault, they are frequently defined only for an operating duration of 20 s, during which the fault must be cleared. If this time is exceeded, a relay before the load resistor ensures its clearing.

With now sufficient earth current, the necessary settings for directional earth-fault protection can be defined:

No.	Parameter	Value
3300	DISPLACEMENT VOLTAGE PROTECTION VE>	
3309	Displacement voltage level Ve>	0.10 U/Un
3311	Delay time for annunciation of VE>	1.00 s
3312	Delay time T-UE of the UE> stage	10.00 s

The displacement voltage V_E is set to 0.1 V_N, thus ensuring that V_E enables direction detection even at the lowest possible fault current and zero voltage. 3312: Normally, V_E is only signalled.

No.	Parameter	Value
3100	DIRECTION OF SENSITIVE EARTH	
3102	Second. current I1 for max. error angle of C.T. I1	0.010 I/In
3103	Error angle of C.T. at I1	0.3 deg
3104	Second. current I2 for max. error angle of C.T. I2	0.100 I/In
3105	Error angle of C.T. at I2	0.3 deg
3115	Dir. IEE>> stage of high-sensitivity E/F prot.	Forwards
3122	Dir. IEE> stage of high-sensitivity E/F prot.	Forwards
3123	Operating direction of the IEE> or IEEp stage	0.010 I/In
3124	Correction angle for direc. determination	5.0 deg
3125	Measurement mode for direc. determination	Cos phi
3126	Drop-off delay for dir. stabilization	1 s

Current transformer phase angle errors are entered at the addresses 3102 to 3105. This is particularly important in compensated power systems. In isolated systems like the one in this example, extremely precise measuring current transformers can be dispensed with. 3115 and 3122 specify the tripping direction. The type of direction determination is specified with 3125. Generally, the following applies: “sin phi” for isolated systems and “cos phi” for compensated systems. Here, “cos phi” was set because the resistive amount in the fault current through the earthing transformer is about ten times as high as the capacitive amount. Thus, the fault current assumes an resistive-capacitive character. 3124 is a parameter for rotating the direction characteristic on the basis of Par 3125 by a specific angle. With a resistive current of I_{Ep} = 0.6 A and a capacitive current of I_{EC} = 0.0561 A, the resulting angle is 5 degrees (arctan 0.0561/0.6). 3124 is therefore set to + 5°, which is the capacitive direction. This angle is constant in a very good approximation and is not dependent on whether the fault is inside or outside the stator winding.

No.	Parameter	Value
3000	EARTH FAULT IN COMPENSATED/ ISOLATED NETWORKS	
3001	High-sensitivity earth-fault protection	on
3013	IEE>> stage of high-sensitivity E/F prot.	0.010 I/In
3014	Delay time T-IEE> of the IEE>> stage	0.5 s
3015	IEE> stage of high-sensitivity E/F prot.	+ * I/In
3016	Pickup value of high-set stage IEE>> (dy)	+ * I/In
3017	Pickup value of O/C stage IEE> (dyn)	+ * I/In
3018	Delay time T-IEE> of the IEE> stage	5.00 s
3019	Measurement repetition for E/F pickup	no
3028	Manual close	IE>> undelayed

The I_E>> stage is used for the current threshold (Par 3013). A tripping time that is not too short is recommended to reduce inaccuracies as a result of transients (starting current of the motor or transients on the occurrence of an earth fault). In this case: 0.5 s (Par 3014)

The resulting direction characteristic with vectors for the zero current and voltage is shown in Fig. 10.

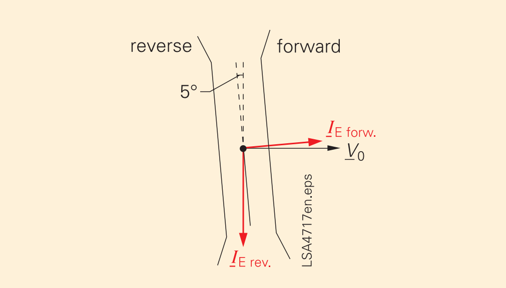


Fig. 10 Adjustment of the direction characteristic to the resistive-capacitive fault current. It should be set so that the earth current in the forward direction is perpendicular to the direction characteristic.

c) Compensated power system

In the compensated or resonant-earthed power system, the fault current at the fault location is reduced with the help of a coil matched to the system's phase-earth capacitances, the so-called Petersen coil, so as to enable self extinction of the arc.

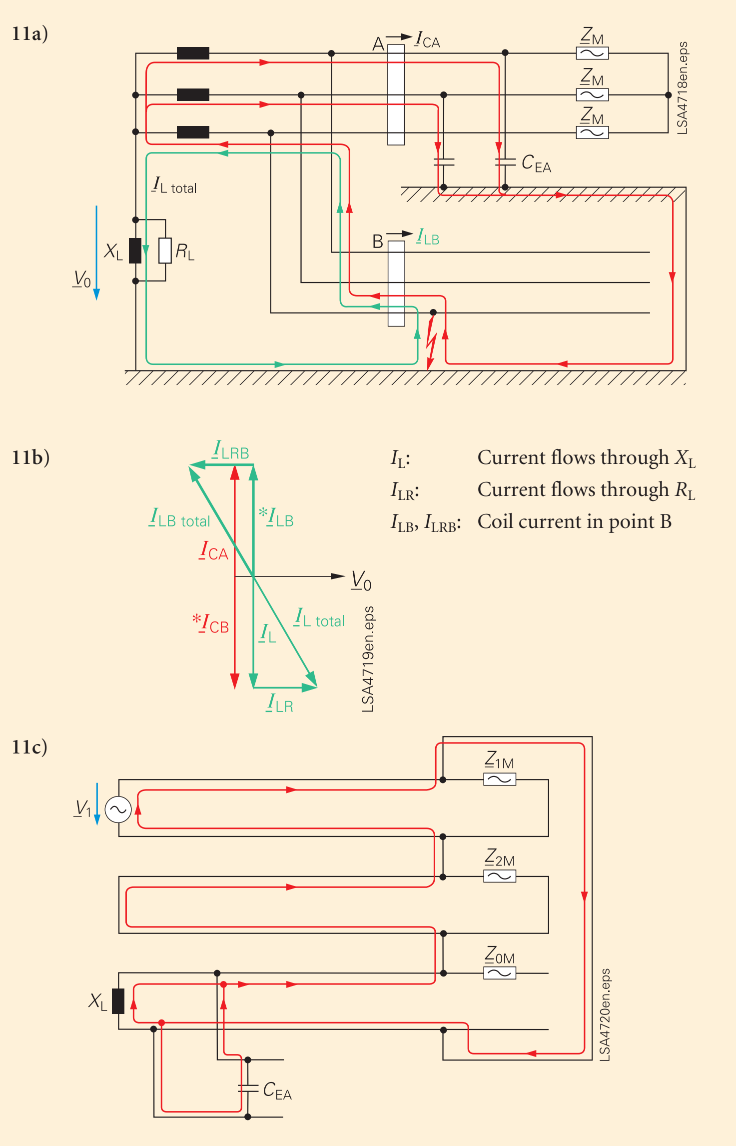


Fig. 11 Schematic diagrams of compensated or resonant-earthed system

In a compensated power system the capacitive current in a faulted feeder is already low and further reduced by the parallel-connected zero reactance of the Peterson coil. Therefore no (selective) protection can be provided with the aid of a current criterion. Instead, the so-called "wattmetric residual current method" or the cos phi method is applied.

As the total zero sequence current in B (Fig. 11) either leads or lags depending on compensation, which may also change during operation due to disconnection of grid parts, the phase angle of the capacitive/inductive zero current is not a reliable criterion. Instead, the resistive current is assessed. This is the amount of the fault current that is caused by the resistive amount of the Petersen coil's reactance and is only to be found in the faulty feeder. As this current is very low in comparison with the inductive coil current (in the order of magnitude of a few percent), sometimes an ohmic resistor is connected in parallel with the coil so that sufficient resistive current is flowing for an earth fault at 80 % of the stator winding.

Since the resistive currents are very low, it is imperative to use a core-balance current transformer. A Holmgreen circuit would falsify the result of measurement to an inadmissible extent. To correct the phase angle error of the core-balance current transformer, it is possible to enter a few fault-current pairs of the core-balance current transformer in the 7SJ 602.

No.	Parameter	Value
3000	EARTH FAULT IN COMPENSATED/ ISOLATED NETWORKS	
3001	High-sensitivity earth-fault protection	on
3013	IEE>> stage of high-sensitivity E/F prot.	0.014 I/In
3014	Delay time T-IEE> of the IEE>> stage	0.50 s
3015	IEE> stage of high-sensitivity E/F prot.	+ * I/In
3016	Pickup value of high-set stage IEE>> (dy)	+ * I/In
3017	Pickup value of O/C stage IEE> (dyn)	+ * I/In
3018	Delay time T-IEE> of the IEE> stage	5.00 s
3019	Measurement repetition for E/F pickup	no
3028	Manual close	IE>> undelayed

3013: It is assumed that the residual resistive current amounts to at least 10 mA. If necessary, the Petersen coil must be connected in parallel with an ohmic resistance to achieve this value.

No.	Parameter	Value
3100	DIRECTION OF SENSITIVE EARTH	
3102	Second. current I1 for max. error angle of C.T.	0.010 I/In
3103	Error angle of C.T. at I1	0.3 deg
3104	Second. current I2 for max. error angle of C.T.	0.100 I/In
3105	Error angle of C.T. at I2	0.3 deg
3115	Dir. IEE>> stage of high-sensitivity E/F prot.	Forwards
3122	Dir. IEE> stage of high-sensitivity E/F prot.	Forwards
3123	Operating direction of the IEE> or IEEp stage	0.010 I/In
3124	Correction angle for direc. determination	5.0 deg
3125	Measurement mode for direc. determination	Cos phi
3126	Drop-off delay for dir. stabilization	1 s

3102 to 3105 serve to correct the aforementioned current transformer errors. 3123 is the minimum current threshold as from which direction determination is performed. 3125 defines the cos phi measurement, i.e. the residual resistive current in the fault current is assessed. In this case, 3124 remains set to 0° because only the resistive amount of the fault current is assessed.

Summary

The earth-fault protection of the motor must be designed with the appropriate SIPROTEC 7SJ602 according to the earthing of the system star point. With the use of earthing transformers or core-balance current transformers the sensitivity is adequate for sure detection of a fault, even if the fault currents are very low.

Protection of Medium-Power Motors

Motor settings using the SIPROTEC relay 7SJ62 is explained below. Information is given on how to use the motor's existing technical data to derive meaningful settings. Among other things, dynamic parameter changeover to reduce overcurrent settings during normal operation is explained. As an option, an external RTD-box can be used to directly monitor the stator and bearing temperatures via temperature sensors.

■ 1. SIPROTEC 7SJ62

The SIPROTEC time-overcurrent relay 7SJ62 offers motor protection functions for medium-power motors with the following scope in one of the available ordering variants:

Fig. 1 SIPROTEC 7SJ62 and 7SJ63/7SJ64 relays

Protection functions	Abbreviation	ANSI
Time-overcurrent protection (phase/earth)	$I >>, I >, I_p, I_E >>, I_E >, I_{Ep}$	50, 51, 50N, 51N
Directional earth-fault detection	$I_{EE} >>_{dir.}, I_{EE\ dir.} >>, V_E/V_o >$	67N, 51Ns, 59N
Thermal overload protection	$I^2 t >$	49
Starting time supervision	$I_{start}{}^2\ t$	48
Restart inhibit for motors	$I^2 t$	66, 49R
Negative-sequence protection	$I_2 >$	46
Undervoltage	$V <$	27
Temperature monitoring	ϑ (RTD-box)	38

Besides 7SJ62, the 7SJ63 or 7SJ64 can also be used.
The differences between these devices and the 7SJ62 are:

7SJ63:

Same functions as 7SJ62 and also

- Large graphical feeder control display
- Comfortable on-site device operation for control
- Key switch
- Large number of binary inputs and outputs

7SJ64:

Same as 7SJ63 and additionally

- Higher PLC/CFC logic program performance
- Flexible protection functions
- Additional rear interface (separate connection of the RTD-box and rear DIGSI interface possible)
- A fourth voltage input for measuring the displacement voltage or for synchro check function

■ 2. Available motor data

Not all data is available in our example. Unfortunately, this all too frequently reflects reality, for example when a motor has been in operation for a very long time and complete documentation is no longer available or only the data on the motor's rating plate is available.

Given:
Compressor motor for compressed air in an industrial plant:

Size	Value
Power	780 kW
Rated voltage	10 kV
Motor rated current	54 A
Max. starting current (at 100 % V_N)	250 A
Starting time (at 100% V_N)	5 sec
Heating time constant	40 min
Cooling time constant at standstill	140 min
Max. continuous thermal rating current	60 A
Max. blocked rotor time	10 sec

■ 3. General power system data

The current and voltage transformer data and the type of connection are entered in the unit under "System Data 1".

Current transformer 75 A/1 A
Core-balance current transformer 60 A/1 A
Voltage transformer 10 kV/100 V
Insulated power system

No.	Parameter	Value
0213	Voltage transformer connection	U12, U23, UE
0204	Transformer rated current, phase primary	75 A
0205	Transformer rated current, phase secondary	1 A
0217	Transformer rated current, earth primary	60 A
0218	Transformer rated current, earth secondary	1 A
0202	Transformer rated voltage prim.	10 kV
0203	Transformer rated voltage secondary	100 V

■ 4. *Starting time monitoring*

The setting parameters for monitoring the starting time require the starting current and the starting time. In our example, the blocked rotor time is not critical because it is longer than the starting time (10 sec in comparison with 5 sec). The associated setting parameter for the blocked rotor time is deactivated (key in a lower-case “o” twice for infinite). The starting time monitoring function can quickly respond to a blocked rotor and external wiring with a speed monitor is dispensed with.
As the guaranteed starting time (5 sec) is specified in the technical data, the protection setting must lie above it. In our specific case, the value 7 sec was chosen. Taking the current transformer ratio into account, the maximum starting current is calculated as $I_{\text{start}} = 250\text{ A}/75\text{ A} = 3.33$.

No.	Parameter	Value
4102	Maximum startup current	3.33
4103	Maximum startup time	7 sec
4104	Locked rotor time	oo

■ 5. *Overload protection*

Typical characteristic quantities designate the overload function, namely: maximum permissible continuous operating current, heating (heat-gain) time constant and cooling time constant at standstill. The maximum current is often not specified in the technical data. According to experience, a setting 10 % above $I_{\text{N, M}}$ can be used and, in our case, $I_{\text{M, max}} = 60$ A is already specified. Under parameter 4202,
k factor = $I_{\text{M, max}} / I_{\text{CT. prim}} = 60\text{ A}/75\text{ A} = 0.8$ is set.

The 40 min heating time constant can be adopted directly as the setting. The overload protection function also takes cool-down behaviour into account because different prerequisites for the motor (with or without fan) produce differing cool-down behaviour. The value is set under parameter 4207 A as a heating to cooling factor, i.e. 140 min/40 min = 3.5.

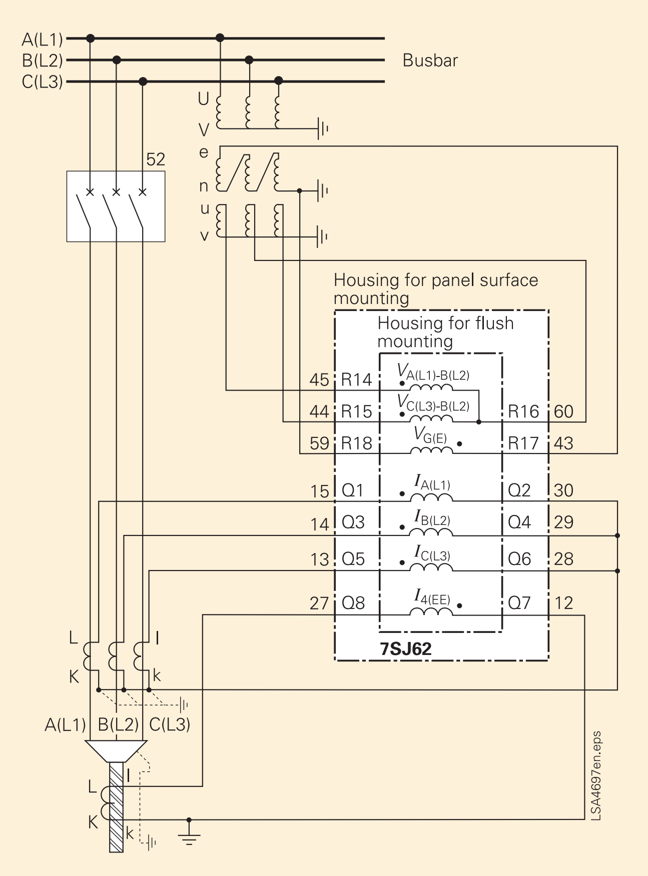


Fig. 2 7SJ62 connection diagram

The thermal warning stage, parameter 4204, offers an additional warning before tripping. This is why it should be set to below the 100 % tripping threshold, for example 90 %. If you want to know how high the thermal value already is at rated current, calculate

$$1/k^2 = 1/(1.1 \cdot 1.1) = \frac{1}{1.2} = \text{approximately } 0.83,$$

i.e. approximately 83 % at
$I_N = (54\text{ A}/75\text{ A})\ 1\text{ A} = 0.72\text{ A}$ sec.

The chosen current warning stage can be set to equal the maximum current.

Parameter 4208A, dropout time after emergency starting, is active only if coupling in via a binary input has been realized, so as to allow emergency starting for the overload protection function despite the presence of an overload TRIP signal.

No.	Parameter	Value
4202	k factor	0.8
4203	Time constant	40 min
4204	Thermal alarm stage	90 %
4205	Current alarm stage	0.8
4207 A	Kt time factor at motor standstill	3.5
4208 A	Dropout time after emergency starting	100 sec

Under System Data 2 there is an important parameter that defines the interplay of overload protection and starting time monitoring (parameter 1107). The overload protection function is active up to this setting, the device detects higher current values as motor starting, the starting time monitoring function runs and the thermal overload model does not increase any further. It is advisable to set the value to approximately 50 % of the starting current (in our case 250 A/2 = 125 A, taken into account as the secondary value with the current transformer ratio of 75 A/1 A = 1.66 A). Thus, starting at low rated voltage is detected and protection is provided against sufficiently high overloads above the maximum current (110 % of I_N).

No.	Parameter	Value
1107	Motor starting current (blk overload)	1.66 A

Direct measurement of temperatures

Up to two RTD-boxes with a total of 12 measuring points can be used for temperature detection and these can be detected by the protection unit. Thus, the thermal state can be monitored, in particular on motors, generators and transformers. The bearing temperatures of rotary machines are also checked to detect when limit values are exceeded. Temperatures are measured by sensors at different points on the protected object and are fed to the unit through one or two RTD-box (es) 7XV566.

As an alternative, the ambient or coolant temperature can be fed to the overload protection function via the RTD-box. To this end, the necessary temperature sensor must be connected to sensor input 1 of the first RTD-box. As all calculations are run with scaled quantities, the ambient temperature must also be scaled. The temperature at rated current is used as the scaling quantity. If the rated current deviates from the rated transformer current, the temperature must be adjusted with the help of the following formula under parameter 4209, “temperature at rated current”.

$$\vartheta_{\text{Nsecondary}} = \vartheta_{\text{N, M}} \cdot \left(\frac{I_{\text{Nprim}}}{I_{\text{N, M}}} \right)^2$$

For example $\vartheta_{\text{N, M}} = 80$ °C
(obtained by measurement),
then $\vartheta_{\text{Nsecondary}} = 80$ °C $(75/54)^2 = 153$ °C

Fig. 3 RTD-box 7XV5662-xAD10

No.	Parameter	Value
4209	Temperature rise at rated current	153 °C

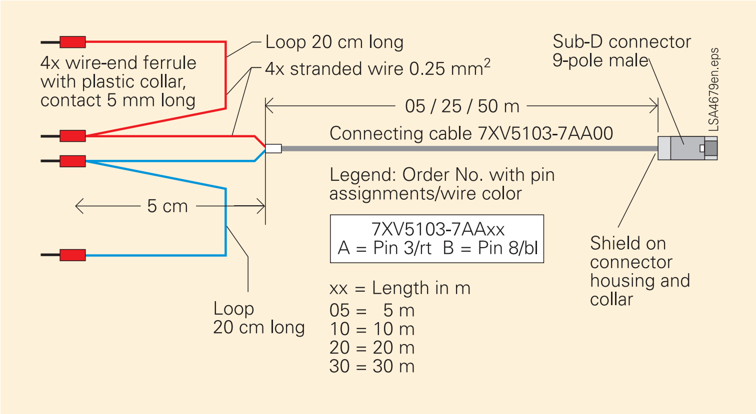


Fig. 4 Connecting cable between SIPROTEC and RTD-box 7XV5103-7AAxx

■ 6. *Restart inhibit*

The second thermal model for motor protection is created in the restart inhibit function for protection of the rotor. The main focus is placed on the number of starts from the cold and warm states. This data is not available in our case and so three cold starts (n_c) and two warm starts (n_w) are assumed.

The rotor temperature equalization time, parameter 4304, is set to 1 min and defines the minimum dead time between individual starts. Parameter 4302, starting current/rated motor current, results in 250 A/54 A = 4.6. The value at which the motor starts with rated torque and rated voltage is selected as starting time. Often, the time is indicated in the starting characteristics supplied. In this specific case starting time is 5 seconds.

If data is not available, the cool-down behavior for the restart inhibit function can be assumed similarly to the cool-down behavior for overload protection. In the case of overload protection, this was 140 min/40 min = 3.5. For the restart inhibit function, this is entered under parameter 4308.

Parameter 4309, “extension of time constant at running”, takes effect when activation of the motor was successful and then the motor continues to run in rated operation. Cooling for this is clearly shorter than under parameter 4308 because rotor operation involves intrinsic cooling and so we choose the factor 2.

After three starts in brief succession, the restart inhibit function then blocks (and issues a release signal after a calculated dead time to enable reconnection once again). The internally calculated dead time depends on the respective load and, accordingly, may differ in length. Alternatively, it is possible to consciously specify a minimum inhibit time (for example, if the customer insists on additional safety factors). This is set under parameter 4310.

No.	Parameter	Value
4302	Starting current/rated motor current	4.6
4303	Maximum permissible starting time	5 sec
4304	Rotor temperature equalization time	1.0 min
4305	Rated motor current	0.72 A
4306	Max. number of warm starts	2
4307	Difference between warm and cold starts	1
4308	Extension time constant at stop	3.5
4309	Extension time constant at running	2.0
4310	Minimum restart inhibit time	6.0 min

■ 7. *Negative-sequence (unbalanced-load) protection*

As no further information is available, recommendation-based values are used. In the case of a definite-time tripping characteristic, these are:

10 % $I^2/I_{N,M}$ for warning or long-time delayed tripping and approx. 40 % $I^2/I_{N,M}$ for short-time delayed tripping.
The setting values have to be converted for the secondary side by using the transformation ratio of the current transformer (75 A/1 A). For parameter 4002 the lowest setting value is 0.1 A.

No.	Parameter	Value
4002	Pickup current I2 >>	0.1 A
4003	Time delay T I2 >>	20 sec
4004	Pickup current I2 >>	0.30 A
4005	Time delay T I2 >>	3 sec

■ 8. Time-overcurrent protection

Only the phase time-overcurrent protection is considered; due to the “isolated power system” earthing, the earth function is covered by the sensitive earth-fault function.
In relation to the phase time-overcurrent protection settings, it must be noted that these must lie above the motor starting values. Due to the short-time occurring motor inrush, the I>> stage must even be set to >1.5 · starting current, and so we choose 1.6 · (250/75) A = 5.33 A. Time delay T I>> (parameter 1802) is selected at 50 ms. Initially the peak value of the starting current may be even higher. With time delay T I>>, non-delayed, set at 0 ms, the I>>-stage should be set with 2.5 · starting current. 1.1 · (250/75) A = 3.6 A is calculated for the I> stage.

If a short-circuit current occurs which lies at 2.5 · $I_{N,\,M}$ due to a contact resistance, the time-overcurrent protection will not pickup but, as shown in Fig. 5, will trigger starting time supervision. Tripping does not occur, however, until after a few seconds (> 7 seconds in our example), which can lead to enormous damage.

It is now possible to reduce the definite-time overcurrent-time settings during rated motor operation, so as to be able to respond more sensitively to all manner of current faults (see Fig. 6). To this end, the “Dynamic Parameter Changeover” option is used: during the normal state, i.e. when the motor is running, lower settings are valid which may already trigger (with a short delay) in the event of faults as from 1.5 · $I_{N,\,M}$ (depending on overload conditions).

Two criteria are optionally available for detection of the deactivated system and thus changeover to high settings:

- The circuit-breaker position is communicated to the unit via binary inputs (parameter 1702 dynPAR.START = CB position).
- Falling below an adjustable current threshold (parameter 1702 dynPAR.START = current criterion) is used.

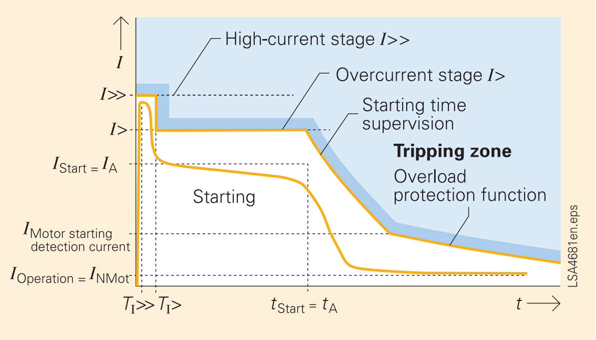


Fig. 5 Coordination of protection functions (without dynamic parameter changeover)

The active time parameter 1704 must be set to higher than the motor starting time. The reduced value for I>, parameter 1204, results from 1.5 · (54/75) A = 1.1 A.

Dynamic parameter changeover:

No.	Parameter	Value
1703	Interruption time	0 sec
1704	Active time	8 sec
1801	Pickup current I>>	5.33 A
1802	Time delay T I>>	0.05 s
1803	Pickup current I>	3.6 A
1804	Time delay T I>	0.2 s

Definite-time overcurrent-time protection:

No.	Parameter	Value
1202	Pickup current I>>	5.33 A
1203	Time delay T I>>	0.05 sec
1204	Pickup current I>	1.1 A
1205	Time delay T I>	1 sec

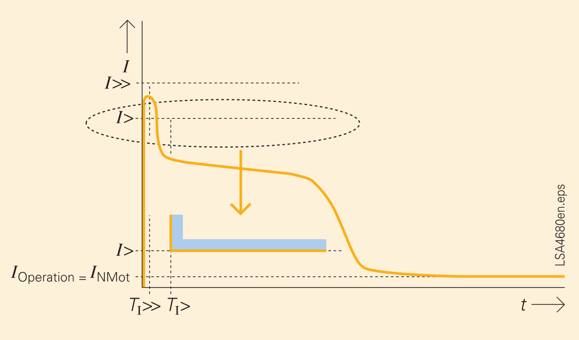


Fig. 6 Reducing the time-overcurrent protection I> stage during rated operation

Additional programming with PLC/CFC logic is not necessary. Changeover takes place automatically. To avoid tripping prematurely with the I> stage 1204 in the event of short-time, substantial overloads (load jam), the tripping time is set to 1 sec.

■ 9. *Sensitive earth-fault detection*

Sensitive earth-fault detection includes a large number of settings, for example to exactly determine the displacement voltage or to correct transformer errors. We will consider only the essential settings for detection of a directional earth fault. The other parameters can remain at default settings. The thresholds for the I_{EE} current must be determined by way of the power system data. To this end, we need the cable lengths and types to calculate the capacitive earth current $I_{CE.}$

Sometimes a load resistor is also connected upstream, so as to arrive at an increased earth-fault current in the event of a displacement voltage. Let us assume a capacitive earth current I_{CE} of 20 A. For a protection range of 90 %, the protection should already operate at 1/10 of the full displacement voltage (parameter 3109 with $0.1 \cdot 100\ V = 10\ V$), where also only 1/10 of the earth-fault current results.
Therefore, $(20\ A/(60\ A/1\ A))\ 0.1 \approx 0.035\ A$ is set for parameter 3117.

With regard to determining the direction, note that the earth current flows in the direction of the protected motor when parameter 3122 set to "forward" and parameter 0201 "current transformer star point" in direction of "line" are selected and the earth transformer is connected as shown in Fig. 2.

No.	Parameter	Value
3113	Pickup current IEE>>	0.5 A
3114	Time delay T IEE>>	oo
3117	Pickup current IEE>	0.035 A
3118	Time delay T IEE>	5 sec
3109	Ven> measured	10 V
3122	Direction IEE>	Forward
3125	Measurement method	Sin. Phi

■ 10. *Voltage protection*

The motor still has to cope with up to about 80 % of the rated voltage and values below that lead to instability.

No.	Parameter	Value
5103	Pickup current U<	75 V
5106	Time delay T U<	1.5 sec
5111	Pickup current U<<	70 V
5112	Time delay T U<<	0.5 sec

■ *Summary*

The motor protection functions of the SIPROTEC 7SJ62 derived from the current and voltage inputs result in a combination that offers users effective and low-cost all-round protection and which is very frequently utilized for medium-voltage motors in industry. Steps for transferring the motor data to 7SJ62 setting data were discussed and the substitute settings suitable for characteristic motor variables were proposed.

Protection of High-Power Asynchronous Motors

To minimize impacts on the system to the greatest extent possible when starting motors, high-voltage motors are often switched in via a starting process. Various processes have an influence on the design of protection. This chapter works out the protection setting, taking reduced voltage starting via a starting transformer into account.

■ 1. Device selection

An expedient mix of functions is needed to protect a motor against the various kinds of faults. Design should be based not only on the motor's power output, but also on the importance of the drive for the technological process, the operating conditions and the requirements of the motor manufacturer.
The motor in this example has a rated power of 3 MW. For this size of motor, it is advisable to use fast short-circuit protection in the form of differential protection, which is performed by a SIPROTEC 7UM62 for asynchronous motors.

Other protection functions recommended for a motor of this power rating are:

Protection functions	Abbreviation	ANSI
Stator thermal overload protection	I^2t	49
Restart inhibit for rotors	I^2t	66, 49R
Motor starting time supervision	$I_{start}{}^2t$	48
Negative-sequence (unbalanced-load) protection	$I_2>$	46
Earth-fault protection	$V_0>$	59N
Differential protection	$\Delta I>$	87M

Transformer protection is not discussed in this chapter and must be set up separately with additional hardware. This can be done with a second 7UM62, for example, which is set as transformer differential protection. Savings in terms of spare-parts stocking can be achieved by using uniform hardware.

Transformer differential protection relay 7UT6 is another possibility for protecting the transformer. In the case of a remote transformer outside the protected zone, the line differential protection relay 7SD610 can be used with the additional function (transformer in the protected zone).

■ 2. Connection

As shown in the following single-pole overview diagram (Fig. 1), the asynchronous motor is connected to a Yd5 transformer in unit configuration. With a view to the power system conditions, the starting current I_A should be kept low and this is why the motor is started via reduced voltage starting by means of the so-called three-switch method or the Korndorfer circuit. The machine voltage is stepped down during starting by means of a starting transformer (autotransformer). As soon as the motor has reached a certain speed, the transformer is bypassed with Q2 and the motor is switched to the full power system voltage.

Starting takes place as described below:

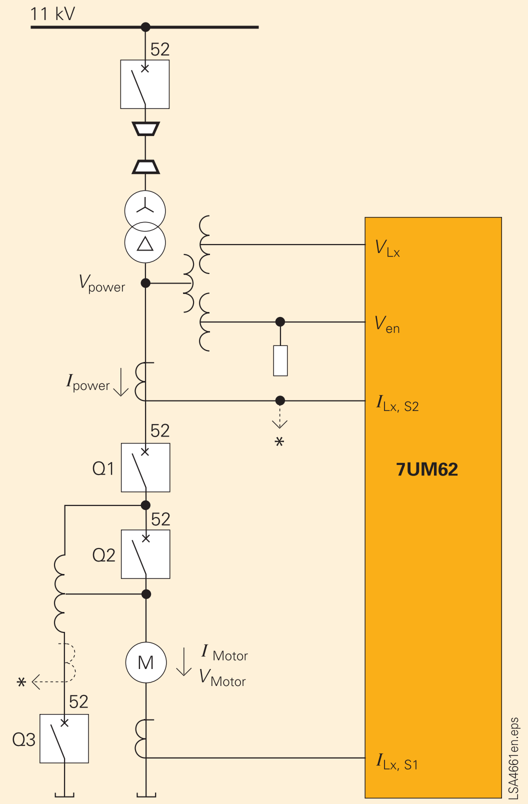
1) Q3 closed
2) Via Q1, the starting transformer is switched into the power system and runs at a reduced voltage.

The motor voltage is taken off a center tap of the starting transformer and is as follows:

$$V_M = \frac{n_2}{n_1} V_{\text{power system}}$$

$\frac{n_2}{n_1}$ = winding ratio of starting transformer

Via the starting transformer, the motor voltage can be stepped down to such an extent as is permissible with a view to the opposing torque during starting. The starting current from the power system also decreases in the same ratio as the starting torque.



* *Optionally, an additional current transformer can be used at the starting transformer's star point. This is discussed in the section on differential protection.*

Fig. 1 Single-pole overview diagram

The current consumption from the power system during starting is as follows:

$$I_{\text{power system}} = \frac{n_2}{n_1} I_M$$

and is limited via the starting transformer's transformation ratio.

3) In the next starting phase, Q3 is opened and the motor is powered from the system via the starting transformer's series inductance.
4) Once the motor has reached the specified speed, Q2 is closed and the motor is operated at the full power system voltage.

3. Available data

Transformer

Current transformer, star point end	650 A/1 A
Current transformer, feeder end	650 A/1 A
Voltage transformer	$\frac{3.3\text{ kV}}{\sqrt{3}} \Big| \frac{100\text{ V}}{\sqrt{3}} \Big| \frac{100\text{ V}}{3}$

Motor

Dimension	Value	
Rated power	3000 kW	
Rated voltage	3300 V	
Rated current	591 A	
Idle current	93 A	
Thermally permissible continuous current	650 A	
Thermal stator time constant	12 min	
Cooling stator time constant	60 min	
Permissible starts from the cold state	3	
Permissible starts from the warm state	2	
	100 % V_N	57 % V_N
Starting current	6.7 I_N	3.7 I_N
Starting time	5 sec	28 sec
Locked rotor time, cold machine	5 sec	29 sec
Locked rotor time, warm machine	4 sec	21 sec

Starting transformer

Primary voltage	3300 V
Secondary voltage	2362 V

4. Protection functions applied

The various protection functions are described below. The settings are specified as secondary values. The focus is on the differential and earth-fault protection functions. Protection functions that protect a motor against thermal overloading are described in depth in the chapter entitled “Thermal stress of motors and necessary protection functions”.

4.1 Differential protection

Differential protection provides fast short-circuit protection for the motor. The principle of measurement is based on a comparison of all currents flowing into the protected object (Kirchhoff’s current law). The direction of the counting arrows is defined so that currents flowing in the direction of the protected object are counted as positive.

In Fig. 2, the following results for the differential current:

$$\Delta I = I_{\text{diff}} = \left|\underline{I}_1 + \underline{I}_2\right|$$

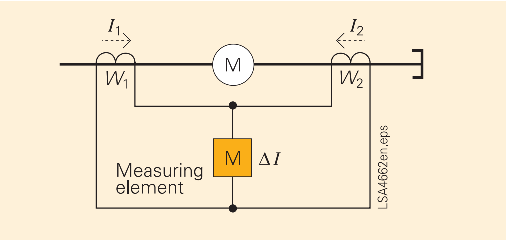


Fig. 2 Basic principle of differential protection on the motor (single-phase depiction)

If very large currents flow through the protected zone at the moment of switching on, a corresponding differential current arises in the measured element **M** with differing transfer behavior in the saturation range of the current transformers **W1** and **W2**, and this can cause tripping. A stabilizing current I_{stab} is additionally introduced to avoid such over-functioning of the protection.

$$I_{\text{stab}} = \left|\underline{I}_1\right| + \left|\underline{I}_2\right|$$

A differential protection characteristic (Fig. 3) consisting of four branches a, b, c and d is defined via the differential and stabilization current.

Pickup of the differential protection takes place in two stages. In addition to the pickup threshold $I_{\text{diff}}>$, a second pickup threshold has also been introduced. If this threshold ($I_{\text{diff}}>>$) is exceeded, tripping is effected regardless of the amount of the stabilization current.

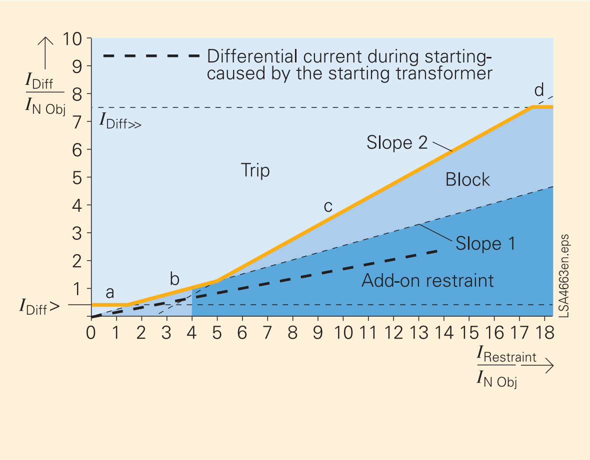
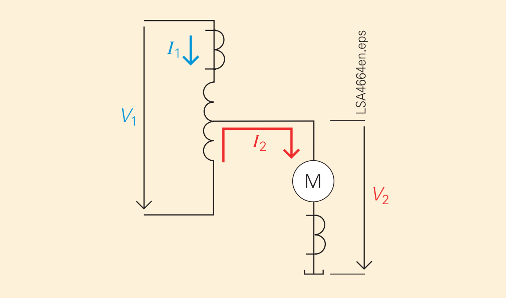


Fig. 3 Tripping characteristic of the differential protection with fault characteristic

The starting process of a motor via a starting transformer must be considered in greater detail. Due to the transformation ratio of the starting transformer during starting, the following applies:

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



$$I_{\text{diff}} = \left|\underline{I}_1 + \underline{I}_2\right| = \left|I_2 - \frac{V_2}{V_1} \cdot I_2\right| = \left(1 - \frac{V_2}{V_1}\right) \cdot I_2$$

$$I_{\text{stab}} = \left|\underline{I}_1\right| + \left|\underline{I}_2\right| = \left|-\frac{V_2}{V_1} I_2\right| + \left|I_2\right| = \left(\frac{V_2}{V_1} + 1\right) \cdot I_2$$

It is necessary to check whether the differential current caused by the starting transformer during starting leads to tripping. The differential current profile is as follows:

$$\frac{I_{\text{diff}}}{I_{\text{stab}}} = \frac{1 - \frac{V_2}{V_1}}{\frac{V_2}{V_1} + 1} = \frac{1 - \frac{2362\ \text{V}}{3300\ \text{V}}}{\frac{2362\ \text{V}}{3300\ \text{V}} + 1} = 0.166$$

and is plotted into the characteristic diagram (Fig. 3) as a broken line. The characteristic shows that the differential current is always in the characteristic’s inhibition range – despite the existing differential current, the differential protection is stable during starting and can therefore also be switched to the active state during starting.

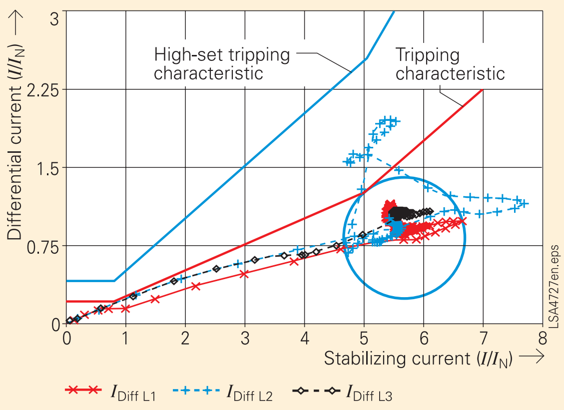


Fig. 4 Differential currents during motor starting (approx. 5 sec) (recorded differential and stabilization currents evaluated with

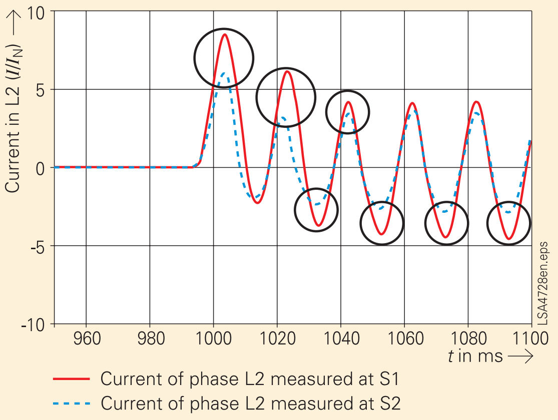


Fig. 5 Depiction of the reason for the differential current transformer saturation in phase L2 of side 2 (evaluated with Mathcad)

Fig. 4 shows the value pairs from a recorded instantaneous value record from this motor in the tripping diagram of the differential protection. The curve reflects the calculated curve of the differential current – the fault current moves along the “straight line” into the quasi-stationary operating point (blue circle).

Still during starting, current transformer saturation (see Fig. 5) occurs in the phase L_2 (characteristic shown in +++) due to high starting currents, with an extreme rise in the differential current, the result being that the operating point moves into the tripping zone above the tripping characteristic shown, in the worst case entailing unintentional tripping of the differential protection.

To avoid overfunction during this mode of operation, the differential protection’s pickup value can be increased at the moment of starting. For protection of a motor, it is recommended to increase the differential protection characteristic by a factor of two during starting. In Fig. 4 we can see that the differential current does not exceed the raised tripping characteristic. The differential protection remains stable.

Fig. 5 shows the instantaneous value curves of the currents for the phase L_2. The saturation response is clearly evident after the first two sinusoidal curves; the reason being DC components in the starting current. Even though identical current transformers are applied, different current transformer burden cause divergent transmission performance with a differential current (see Fig. 4).

In Fig. 6, the motor's starting current (positive-sequence system) is shown in the top curve *I*1 as an r.m.s. value record of side 2 (motor's feeder side). The recording took place during commissioning of the motor with the protection relay 7UM62. The starting current follows a typical curve. The current peak at approximately 21.5 sec, caused by compensation phenomena during shorting of the starting transformer (closure of Q2), is conspicuous.

The duration of the pickup increase should be maintained beyond this time. The sensitivity of differential protection is reduced by activation of the pickup value increase. An additional current transformer at the starting transformer's star point is needed (see note for Fig. 1) if the full sensitivity is not to be dispensed with. The current transformer's secondary side is inversely connected in parallel with the current transformer of side 2 (connection side), thus correcting the current on the connection side. As a result, the correct measured values are fed to the differential protection, also during starting, and raising of the pickup characteristic can be dropped – the differential protection also operates during starting with the normal sensitivity.

In the present example, there was no additional current transformer at the starting transformer's star point and raising of the pickup characteristic was chosen to ensure stability of the protection.

During commissioning, it is advisable to set the fault value recording mode to r.m.s. value recording, thus making it possible to record the entire starting operation (≤ 80 sec.) and to recognize such variations.

The 7UM62 begins to automatically record as soon as the stabilization current enters the additional stabilization zone by more than 85 %, with the result that a record is created automatically during every starting operation and does not need to be triggered separately.

To complete commissioning, recording should be changed over to instantaneous value logging, including recording of the differential and stabilization currents.

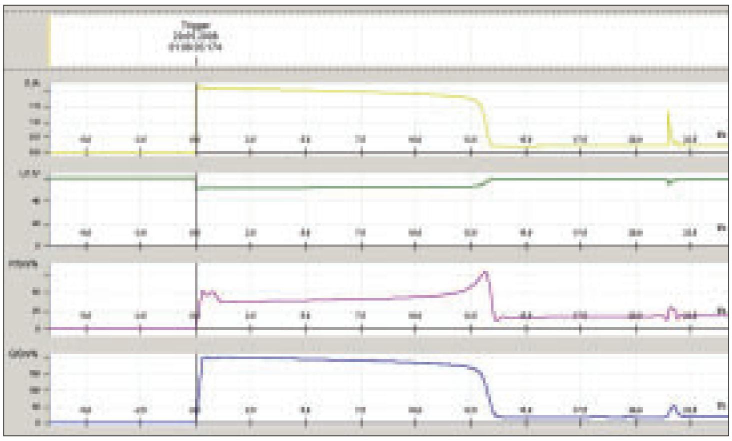


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Fig. 6 Motor starting current (r.m.s. value record from the 7UM62)

Below, the setting parameters for the differential protection function are listed and briefly commented on.

Setting parameters	Value	Comment
I-DIFF> Pickup value of the trip stage IDIFF>	0.20 I/InO	The setting is referred to the protected object's rated current. The 0.20 I/I_{nO} default setting can be retained.
T I-DIFF> Delay time of the trip stage IDIFF>	0.00 s	The delay time **T I-DIFF>** is started if an internal fault in the motor has been detected. The differential protection should normally trip without delay, and so the default setting of 0 sec can be retained.
I-DIFF>> Pickup value of the trip stage IDIFF>>	7.5 I/InO	The **I-DIFF>>** stage is an unstabilized fast tripping stage. As far as the set value is concerned, it must be ensured that the value is not exceeded during normal operation. The setting should be oriented to the maximum starting current (in this case 6.7 I_{nO}).
T I-DIFF>> Delay time of the trip stage IDIFF>>	0.00 s	The **T I-DIFF>>** time is an additional time delay and does not include the relay's inherent operating time delays. The differential protection should normally trip without delay, and so the default setting of 0 sec can be retained.
CH-INCREASED-STARTING Pickup value increase during starting	On	Increasing of the characteristic must be activated with the **CH-INCREASED-STARTING** parameter.
STARTING-STAB Pickup value ISTAB for starting detection	0.10 I/InO	The setting is referred to the protected object's rated current.
STARTING FACTOR Pickup value increase during starting	2	The factor for increasing the pickup values during starting is defined with the **STARTING FACTOR**. A factor of 2 has proven practicable.
MAX. STARTING TIME Maximum starting time	30.0 s	The maximum starting time is specified as 28 s in the motor data. The starting increase should be effective for the entire starting process and this is why a setting of 30 s is chosen.

4.2 Earth-fault protection

An earth fault is caused by a fault on the insulation of a phase to earth.

The motor discussed in this paper is connected in a unit configuration. In this case, evaluation of the displacement voltage has proven a reliable criterion for earth-fault detection. The full displacement voltage V_{E} occurs in the event of a terminal earth fault (Fig. 7).

In the event of an earth fault on the winding, it decreases in proportion to the winding voltage and becomes zero for of an earth fault at the machine's star point.

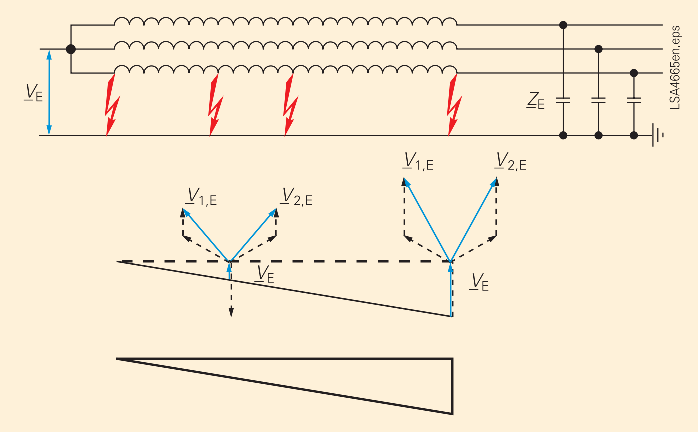
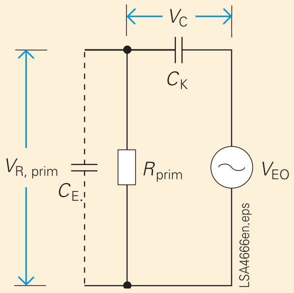


Fig. 7 Displacement voltage V_{E} as a function of the fault location in the event of an earth fault in the machine winding

The chosen setting for the displacement voltage should be very low, so as to achieve the greatest possible protection range on the machine's winding. By contrast, the possible sensitivity of the protection is limited by interference voltages which, in the event of earth faults in the upstream power system, are transmitted to the motor voltage side via the coupling capacitance of the unit-connected transformer.



V_{EO}	Displacement voltage on the HV side
C_K	Total coupling capacitance
R_{prim}	Load resistor *R* referred to the primary side
V_{Rprim}	Interference voltage referred to the primary side of the earthing transformer
V_R	Voltage measured by the protection relay at *R* in the event of an earth fault on the HV side (interference voltage)
TR_{ET}	Limb transformation ratio of the earthing transformer

Fig. 8 Single-phase equivalent circuit ($C_E = C_{generator} + C_{line} + C_{transformer}$ neglected)

The equivalent circuit in Fig. 8 shows that V_{EO} is split up into the voltages V_C and V_{Rprim}. Via the voltage transformer's (earthing transformer's) transformation ratio, V_{Rprim} is transformed to the secondary side (V_R) and represents the interference voltage measured by the relay on the load resistor.

As V_R has to be lower than the relay's pickup value, the chosen load resistor *R* must have a low resistance. A protection range covering about 80 to 90 % of the motor winding is achieved in this way. To achieve a protection range of 80 %, for example, the relay must be set to 20 % of the full displacement voltage V_E.

Dimensioning earth-fault protection with an 80 % protection range

The capacitive resistance of the coupling capacitance C_K is always very much higher than the ohmic resistance of the load resistor *R*. The current transformed to the LV side in the event of an earth fault on the HV side therefore practically depends only on the amount of C_K and V_{EO}.

The dimensioning of *R* is such that V_R is approximately half the pickup value of the earth-fault function that is to be set. This achieves double protection against spurious tripping.

$$I_{Cprim} = V_{EO} \cdot 2\,\pi f \cdot C_K = \frac{11\text{ kV}}{\sqrt{3}} \cdot 2\,\pi f \cdot 10\text{ nF} \approx 0.02\text{ A}$$

- I_{Cprim} Interference current on the primary side of the earthing transformer (voltage transformer)
- V_{EO} Displacement voltage on the HV side of the unit-connected transformer

$$V_{EO} = \frac{11\text{ kV}}{\sqrt{3}}$$

- C_K Total capacitance between the HV and LV sides of the unit-connected transformer (total coupling capacitance between HV and LV) $C_K = 10$ nF (No transformer data sheet available => standard value)

$$I_{Csek} = \frac{1}{3} I_{Cprim} \cdot TR_{ET} = \frac{1}{3} \cdot 0.02\text{ A} \cdot 57.1 = 0.38\text{ A}$$

- TR_{ET} Transformation ratio of the earthing transformer (voltage transformer)

$$TR_{ET} = \frac{\frac{V_N}{\sqrt{3}}}{\frac{100\text{ V}}{3}} = \frac{\frac{3300\text{ V}}{\sqrt{3}}}{\frac{100}{3}} = 57.1$$

- I_{Csek} Interference current on the secondary side of the earthing transformer (voltage transformer)

$$R = \text{SF} \cdot \text{K} \cdot \frac{100\text{ V}}{I_{Csek}} = \frac{1}{2} \cdot 0.2 \cdot \frac{100\text{ V}}{0.38\text{ A}} 26.3\,\Omega$$

- SF Safety factor $V_R \approx 0.5 \cdot$ relay setting
- K 80 % protection range → $\text{K} = 0.2$
- *R* Load resistor

$$P = \frac{V^2}{R} = 380\text{ VA}$$

- *P* Required power of the earthing transformer under loading with *R*

$$I_{R\,max} = \frac{V}{R} = \frac{100\text{ V}}{26.3\,\Omega} = 3.80\text{ A} \quad \text{for } t \leq 20\text{ s}$$

- $I_{R\,max}$ Current via load resistor *R* in the case of 100 % V_E

The following are chosen:

1) Load resistor (for example, with 30 Ω) and an adjustable intermediate tap

2) Voltage transformer with 380 VA for 20 sec load duration

Below, the setting parameters for the earth-fault protection function are listed and briefly commented on.

Setting parameters	Value	Comment
V0 > Starting voltage V0>	20.0 V	The range for earth-fault protection is defined with this setting. A protection range covering 80 % (20 V) to 90 % (10 V) of the stator winding is usual. An increase in the sensitivity also means that the load resistance becomes smaller, and thus also the power of the earthing transformer has to become higher.
T SES Delay time T SES	0.30 s	The maximum loading duration of the loading unit must be taken into consideration when defining the time delay. A time delay of 0.3 sec – 0.5 sec has proven practicable.

4.3 Thermal overload protection

Overload protection prevents thermal overloading of the asynchronous motor's stator winding.

Below, the setting parameters for thermal overload protection are listed and briefly commented on.

Setting parameters	Value	Comment
K-FACTOR Maximum permissible continuous current	1.00	The thermally maximum permissible continuous current I_{max} is described as a multiple of the protected object's rated current I_N: $I_{max\ prim} = k \cdot I_N$ The data sheet indicates a thermally permissible continuous current of 650 A. Values are as follows with the following motor and transformer data: Rated current of the motor $I_{N,\ M} = 591$ A Thermally permissible continuous current $I_{max\ prim} = 650$ A Current transformer 650 A/1 A $\text{K factor}_{set} = k \cdot \frac{I_{N,\ M}}{I_{N,\ CT.\ prim}} = 1.1 \cdot \frac{591\ A}{650\ A} = 1.0$
τ Heating time constant	720 s	Taken from the motor's data sheet – 12 min
Kτ-FACTOR Cooling time constant	5.0	The machine's cool-down behavior at standstill can be taken into account with the Kτ time factor. Taken from the motor's data sheet – 60 min. The default setting of 1 can be retained if different thermal behavior is not to be taken into consideration.
Θ **WARN** Thermal warning stage	90 %	The thermal warning stage issues a warning before the tripping temperature is reached. In the case of the motor discussed with k = 1.1 and adapted rated machine current, the temperature-rise limit value (overtemperature value) is $\frac{\Theta}{\Theta_{TRIP}} = \frac{1}{k^2} = \frac{1}{1.1^2} = 83\ \%$ of the tripping temperature. A setting of 90 % therefore lies above the operationally expected overtemperature of 83 %, but below the tripping temperature of 100 %.

Setting parameters	Value	Comment
I WARN Current warning stage	1.00 A	A current warning stage can be realized in addition to the thermal warning stage. The current warning stage should be set to equal the continuously permissible secondary rated current. $I_{\text{Warn}_{\text{secondary}}} = \text{k} \cdot \frac{I_{\text{N, M}}}{I_{\text{N, CT prim}}} \cdot I_{\text{N, CT secondary}} = 1.1 \cdot \frac{591\ \text{A}}{650\ \text{A}} \cdot 1\ \text{A} = 1.0\ \text{A}$
I LIMIT Limit current of the thermal replica	2.27 A	The limit must be chosen so that, even at the highest possible short-circuit current, the tripping times of the overload protection are reliably above those of the short-circuit protection functions. Limiting to a secondary current that corresponds to approximately 2.5 – 3 times rated machine current is generally sufficient.

4.4 Restart inhibit

Especially when the motor is started, the rotor is subjected to very high thermal stress. Frequent starting of motors can result in thermal overloading. The purpose of the restart inhibit function is to inhibit restarting of the motor.

As the rotor current cannot be measured directly, the rotor temperature is simulated by means of available stator variables and restarting is inhibited if a limit temperature is exceeded.

Below, the setting parameters for the restart inhibit function are listed and briefly commented on.

Setting parameters	Value	Comment
IStrt/IMot.rated Starting current/ motor rated current	3.7	The starting current parameter is entered as the ratio to the rated motor current (**IStrt/IMot.rated**). For correct interpretation, it is important for the apparent power **SN GEN/MOTOR** and the rated voltage **VN GEN/MOTOR** of the motor to be set correctly in the system data 1. The current in the case of the longest starting time is taken from the motor's data sheet. This is the value at the reduced voltage. On the data sheet, the current and the starting time are specified at a voltage of 57 % V_N.
T Starting MAX Maximum permissible starting time	28 s	Taken from the motor's data sheet – the time chosen must correspond to the entered starting current.
n-WARM Permissible number of warm starts	2	Taken from the motor's data sheet.
n-COLD<-> n-WARM Difference between warm and cold starts	1	Taken from the motor's data sheet.
T COMPENSATION Rotor temperature equalization time	1 min	No values are specified on the motor's data sheet. It is recommended to leave the default setting as it is. See also the chapter entitled "Thermal stress of motors and necessary protection functions".
Kτ-OPERATION Extension of the time constant τ_L during operation	2	While the motor is running, heating up of the thermal rotor replica is calculated with the time constant τ_L worked out on the basis of the motor's characteristic values. Requirements for slower cooling: cooling is generated with the time constant $\tau_L \cdot$ **Kτ–OPERATION**. The present motor's data sheet does not specify any details of a rotor time constant. In this case, it is recommended to leave the default setting **Kτ-OPERATION** = 2, in which case cooling takes twice as long as heating up.

Setting parameters	Value	Comment
Kτ-STANDSTILL Extension time constant τ_L at stop	5	To correctly take into account the lower heat dissipation of self-cooled motors at motor standstill, the cooling time constant at standstill $\tau_L \cdot$ **Kτ–STANDSTILL** can be entered separately. The present motor's data sheet does not specify any details of a rotor time constant. In this case, it is recommended to leave the default setting $K\tau = 5$, in which case cooling at standstill takes five times as long as heating up. To ensure correct functioning, it is important to correctly set the current threshold to distinguish motor standstill/running **LS I>** (recommendation: $0.1 \cdot I/I_{N, M}$).
T MIN.INHIBIT TIME Minimum inhibit time of the restart inhibit function	12.8 min	Independently of thermal models, the requirement for a minimum inhibit time after exceeding the number of permissible starts can be fulfilled with the **T MIN.INHIBIT TIME**. The parameters are in conformity with the motor manufacturer's specifications. As there are no requirements for the present motor, setting acc. to the thermal replica is possible. $\tau_L \cdot K_\tau$–OPERATION 28 sec $\cdot (3\text{-}2) \cdot 3.7^2 \cdot 2 = 766$ s

4.5 Starting time monitoring

Starting time monitoring supplements the overload function and the starting inhibit function to prevent inadmissible thermal stressing of the rotor due to excessively long starting operations as a result of a locked rotor, for example.

Below, the setting parameters for starting time monitoring are listed and briefly commented on.

Setting parameters	Value	Comment
STARTING CURRENT Motor's starting current	3.07 A	Starting time monitoring operates with the measured values of side 2. Starting takes place via a starting transformer, this must be taken into account when setting the parameters. $I_{\text{start reduced}} = \left(\frac{2362\text{ V}}{3300\text{ V}}\right)^2 \cdot 6.7 \cdot \frac{591\text{ A}}{650\text{ A}} \cdot 1\text{ A} = 3.07\text{ A}$
MAX. STARTING TIME Permissible starting time of the motor	18 s	The setting for the maximum starting time in accordance with the starting characteristic shown in Fig. 6. Starting takes approximately 14 sec. At 18 sec, a slightly higher setting is chosen.
I STRT. DETECT Starting detection current threshold	1.50 A	The threshold must lie above the maximum load current (load peaks must be taken into account) and below the minimum starting current. In the present example, starting detection is set to above the continuously permissible current and below the expected starting current. 1) Continuously permissible current: $I_{\text{thermperm}} = \frac{650\text{ A}}{650\text{ A}} I_{\text{N, CT secondary}} = 1 \cdot I_{\text{N, CT secondary}} = 1\text{ A}$ 2) Starting current at $V_M = 2362$ V Assumption: Starting current decreases in a linear fashion $I_{\text{start reduced}} = \left(\frac{2362\text{ V}}{3300\text{ V}}\right)^2 \cdot 6.7 \cdot \frac{591\text{ A}}{650\text{ A}} \cdot 1\text{ A} = 3.07\text{ A}$ **ISTRT.DETECT** setting parameter is set to $\leq 0.5 \cdot 3.07\text{ A} = 1.53\text{ A} \approx 1.5\text{ A}$.
LOCKED ROTOR TIME Motor's locked rotor time	4 s	The setting was taken from the motor's data sheet. As the maximum permissible locked rotor time t_E is shorter than the motor's starting time, a locked rotor must be detected via a speed monitor and read into the protection relay via a binary input (">locked-rotor").

4.6 Negative-sequence protection

An unbalanced load is the result of failure of a phase or asymmetry of the power system voltage. The motor frequently continues to run and, in comparison with three-phase operation, consumes an increased current, which may lead to exceeding of the permissible limit temperature.

The negative-sequence (unbalanced-load) protection of the 7UM62 operates with the inverse current $I2$ – if a parameter-definable threshold is exceeded, the tripping time is started and a TRIP command is triggered after it has elapsed.

Below, the setting parameters for the unbalanced-load protection function are listed and briefly commented on.

■ Summary

The application-oriented function mix of the SIPROTEC 7UM62 in the order variant "asynchronous motor" can be used to advantage for this application. The asynchronous motor is optimally protected with just one multifunction device.

Setting parameters	Value	Comment
I2 PERM. Continuously permissible load unbalance	9.1 %	For the thermal replica, the maximum permissible inverse current $I2_{\text{max.prim}}/I_N$ is crucial. According to experience, it is between 6 % and 12 %. $I2_{\text{perm}} = \frac{I2_{\text{max.prim}}}{I_{\text{N, M}}} \cdot \frac{I_{\text{N, M}}}{I_{\text{N, CT prim}}}$ The machine manufacturer does not specify any values for the maximum permissible inverse current. This is why $I2_{\text{max.prim}}/I_N = 10\ \%$ is chosen. $I2_{\text{perm}} = 10\ \% \cdot \frac{591\ \text{A}}{650\ \text{A}} = 9.1\ \%$
FACTOR K Asymmetry factor K	1.65 s	The asymmetry factor is machine-dependent and represents the maximum time in seconds during which the motor may be stressed with 100 % load unbalance. The conservative $K_{\text{prim}} = 2$ s setting is chosen if the motor manufacturer does not specify any details. The factor K_{prim} can be converted to the secondary side with the following relationship: $K_{\text{secondary}} = K_{\text{prim}} \cdot \left(\frac{I_{\text{N, M}}}{I_{\text{N, CT prim}}}\right)^2 = 1.65\ \text{s}$
T COOL Cooling time of the thermal replica	165 s	The **T COOL** parameter defines the period of time that elapses before the protected object cools to the initial value after stressing with a permissible unbalanced-load **I2 PERM.** If the machine manufacturer does not specify any details, the setting can be found by assuming the cooling and heating times of the protected object as being equal. The following relationship then applies between the asymmetry factor K and the cooling time: $\text{TCOOL} = \frac{K}{\left(\frac{I2_{\text{perm}}}{I_N}\right)^2} = \frac{1.65\ \text{s}}{0.1^1} = 165\ \text{s}$ An asymmetry factor K = 2.4 s and a permissible continuous negative sequence of $I2/I_N = 10\ \%$ result in a cooling time of 240 s.
I2>> Starting current I2>>	60 %	Two-phase operation under rated conditions leads to a negative-sequence current of about 66 %. Due to the power to be produced, it rises and reaches values of 100 %.
T I2>> Delay time T I2>>	3 s	A tripping delay of about 3 sec is recommended to allow for transient phenomena.

Protection of Synchronous Motors

This chapter focuses on protection systems for large synchronous motors. Several references are made to other chapters in this volume in which protection functions also applied to synchronous motors are presented in detail. Thus, this motor protection volume must be studied in its entirety.

■ 1. *Scope of a protection system for motors*

Synchronous motors perform various tasks in plants in the raw materials and processing industry, in power generation systems and in infrastructure facilities. Synchronous motors with a power output up to 50 MW are preferably used when high performance demands are placed on motor operation. Examples are conveying systems in mining or coolant feed pumps in power plants.

With regard to the fundamentals of operation and use of various types of motors, refer to the chapter "Introduction to the principles of synchronous and asynchronous motors". Selected protection functions such as overload or differential protection are dealt with in detail in the chapters "Thermal Stress of Motors and Necessary Protection Functions" and "Protection of High-Power Asynchronous Motors". Their discussions also apply to large synchronous motors.


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Fig. 1 Olikiluoto, Finland, nuclear plant

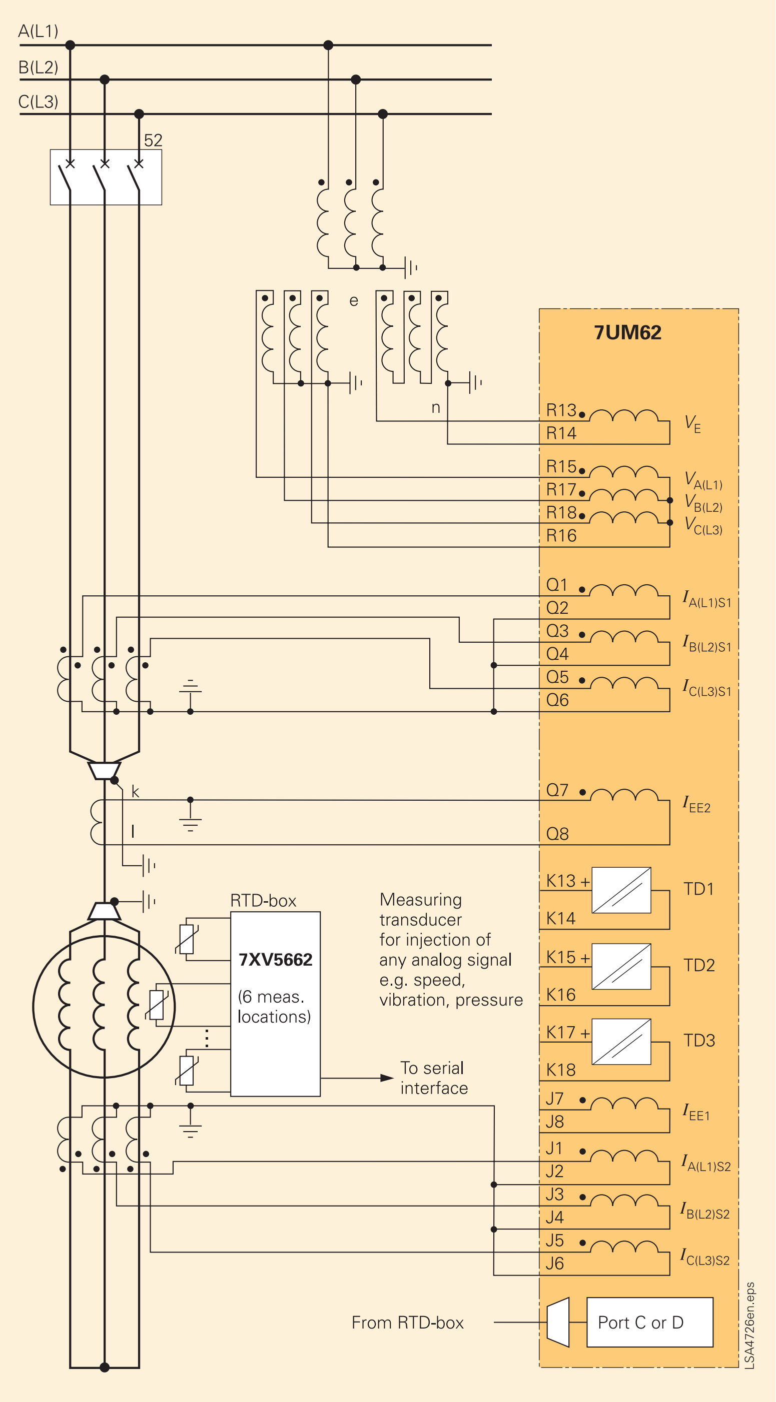


Fig. 2 Connection diagram of motor protection 7UM62

Besides dealing with a few general considerations on the operation and availability of motors, this chapter focuses on further protection functions or types of protection required especially for synchronous motors.

The motor protection function package was implemented specially for large motors in the 7UM62 numerical protection relays. It contains all functions for comprehensive protection of high-power motors.

Fig. 2 shows an example of connection of the 7UM62 protection to a synchronous motor.

The following table contains a summary of the protection functions mainly used for large synchronous motors.

Fault type	Protection function or measurement method	Abbreviation	ANSI No.
Short circuit	Differential protection, time-overcurrent protection	$\Delta I >$ $I > t$	87, 51
Stator earth fault	Directional earth-fault protection Displacement voltage measurement	$I_E >$ $V_0 >$	64, 51N 59N
Stator overload	Overload protection as a thermal replica Temperature measurement via PT100	$I^2 t >$ $\upsilon >$	49 38
Rotor overload	Starting time monitoring Restart inhibit via I^2t Negative-sequence protection	$t = I_{start}$ $I^2 t >_{rotor}$ $I_2 >$	48 66 (49R) 46
Out of step	Underexcitation protection	$1/X_d$	40
Power failure	Undervoltage protection, undercurrent protection	$V <$ $I <$	27 37

Working out an adequate protection system for a motor is oriented to several factors. It goes without saying that the protection engineer strives to protect a motor comprehensively against possible damage, such as thermal overload, or to limit unavoidable damage, such as short circuits, to a minimum. By contrast, protection should not unnecessarily restrict the availability of a motor drive by premature deactivation. Justice is done to this requirement by adapting, as exactly as possible, the protection tripping characteristics to the motors' operating diagrams. Last but not least, the cost-benefit calculation also plays an essential role when it comes to selecting individual protection functions. There should be a healthy relationship between the investment in a protection system and the anticipated costs in the event of motor damage. Besides including the direct repair costs, these also encompass indirect costs such as production outage or possibly even consequential damage to the process plant. This means that the technical scope of a protection system is measured not only by the size and thus the procurement costs of a motor, but also by its importance for a production process.

■ 2. Selected protection functions

2.1. Short-circuit and overload protection

The classic measured electrical value for detecting a fault is the motor's stator current picked up from the feeding three-phase power system. By evaluating the stator current, the electrical protection facility detects a short-circuit in the stator winding, an impending thermal overload of the stator winding or a thermal hazard for the rotor winding due to an imbalance in the three-phase system.

While short-circuit protection limits the damage occurring after an electrical fault, overload protection can avoid damage by detecting the risk early on. This applies equally to negative-sequence protection (unbalanced-load protection) that detects an excessive load imbalance in the feeding three-phase power system and switches off the motor in good time before thermal damage arises.

Differential protection is generally used as fast and selective short-circuit protection. Thanks to the strict selectivity of this measurement principle, extremely short tripping times can be achieved with differential protection, thus attaining optimal damage limitation in the event of short-circuits. This protection facility is presented in the chapter "Protection of High-Power Asynchronous Motors".

Besides differential protection, overcurrent protection, the pickup (response) value of which is above the maximum permissible operating current, is also used for protection against short-circuits. Pickup values of 10 % to 20 % above the maximum operating current are customary. When use is made of definite-time overcurrent-time protection, tripping must be delayed by a time that is more than the motor's permissible startup time. To limit motor damage in the event of high-current short circuits, a second current stage is provided, whose current pickup (response) value lies above the motor's startup current. This high-current stage is provided with a short tripping delay to operation during inrush.

When use is made of inverse-time overcurrent-time protection, the pickup characteristic must be chosen so that it lies above the starting current curve in the current-time diagram. Fig. 3 shows the motor startup current plotted over the starting time. The inverse-time overcurrent characteristic is chosen so that it does not intersect with the starting current curve.

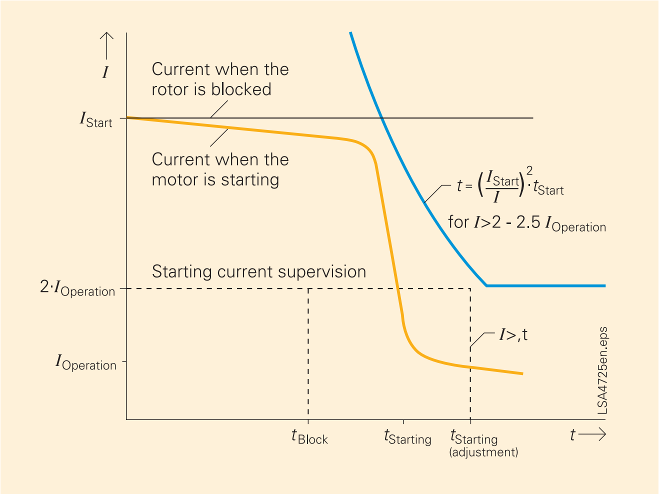


Fig. 3 Starting current with overcurrent-time protection

The advantage of an inverse-time characteristic is that the short-circuit protection tripping time is reciprocal to the amount of the fault current, and so the damage caused by a short circuit on the motor can be better limited. Within the range of low short-circuit currents under twice the rated current, the limit between short-circuit and overload protection is blurred.

A small motor belonging to duty class S1 that is run with a constant load torque can be satisfactorily protected by an overcurrent protection with inverse characteristic against thermal overload. For motors with changing load cycles or intermittent operating belonging to the duty classes S 3 to S 10, a thermal replica with a complete memory is indispensable for cost-effective, safe and reliable operation. Such a thermal replica calculates the motor's present thermal state from the stator current via the cumulated Joule heat in accordance with the formula $\upsilon = k \cdot I^2 t$. The thermal replica exactly records the heating and cooling phenomena linked to load cycles. Compared with simple overcurrent protection, the thermal replica provides optimum protection of the motor against overheating simultaneously with full use of the motor within its operationally permissible limits.

Asymmetries in the feeding three-phase power system can also be the cause of thermal damage on a motor. In accordance with the method of symmetrical components, each three-phase system can be split into a positively rotating positive phase-sequence system, a negatively rotating negative phase-sequence system and a zero system. A symmetrical three-phase system consists of a positive phase-sequence system only. Asymmetries in the three-phase system generate a negative phase-sequence system that induces a rotating field in the motor's rotor circuit. This field rotates, relative to the rotor, at double the frequency in the direction opposite to the rotor's direction of rotation. This opposing rotating field causes strong magnetic losses in the rotor core that can lead to inadmissible temperature rise.

Phase failure is an extreme case of an unbalanced load due to asymmetries. In the case of a two-phase supply, the motor can now only develop small and pulsating torques. As the drive machine's torque requirement generally stays unchanged, in the remaining two phases the motor must accordingly pick up more current, which thermally overloads the windings.

The thermal replica is presented extensively in the chapter on the subject of "Thermal Loading of Motors and Necessary Protection Functions".

2.2 Out-of-step protection

In a protection system for synchronous motors, particular importance is attached to out-of-step protection (protection against loss of synchronism). The characteristic of a synchronous motor is that, during stable operation, the rotor rotates in synchronism with the feeding rotating field. This synchronous operation can be disrupted by two causes.

For one, the synchronous motor can get out of step as a result of underexcitation. This occurs when the exciter power is insufficient for the mechanical power required of the machine. Depending on its design, whenever the exciter power is too low or absent completely the synchronous motor continues to run as an asynchronous motor or it is braked down to standstill.

A second cause of out-of-step condition can be a disturbance in the feeding power system. In the event of a power system short circuit followed by tripping of the fault feeder, the electric drive power from the power system is missing. In accordance with the reactance principle, the motor compensates for this missing electric power for driving the machine by means of a negative acceleration power. It is braked and continues to run with rising slip as an asynchronous motor. Model tests with various synchronous motor construction types have shown that a motor practically always copes well with a brief power system failure of up to approximately 150 ms. During the dead time without voltage, the speed drops to about 95 % of the rated frequency, and thus only so far that the synchronizing torque after the voltage recovers is sufficient to return the motor to synchronous operation. If the motor remains without voltage for longer than 200 ms, in most cases the speed drops so far that the motor falls out of step even when the voltage returns.
The recordings from the aforementioned model tests indicate extreme active and reactive power oscillations in the event of exciter or voltage failure. See Figs. 4 and 5.

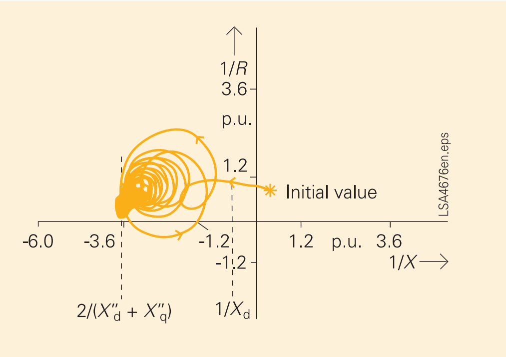


Fig. 4 Admittance in the event of excitation failure (9.88 MVA motor)

Especially at full exciter power, the power oscillation is not attenuated, as can be seen in Fig. 5. The mechanical stress on the motor's shaft, bearings and foundation caused by the active power oscillation calls for deactivation of the motor that has fallen out of step.

In all cases of asynchronous running of a motor studied, be it due to underexcitation or a power system disturbance, the motor oscillation curves in the conductivity diagram are above a susceptance of $1/X_d$.

Consequently, adequate protection in the event of an out-of-step condition, regardless of the cause, is underexcitation protection with a pickup characteristic that runs parallel to the ordinate in the conductivity diagram at $1/X_d$.

In addition to the motor's asynchronous pull-out torque, it is the duration of the voltage failure that crucially influences whether the motor will resynchronize after the voltage returns. The model tests demonstrate that successful resynchronization is completed 500 ms after a short circuit occurs. Returning of the motor to synchronous stable operation can no longer be expected after expiry of this time period. The motor inevitably falls out of step. Therefore, a time setting of about 700 ms is recommended for the out-of-step protection tripping delay.

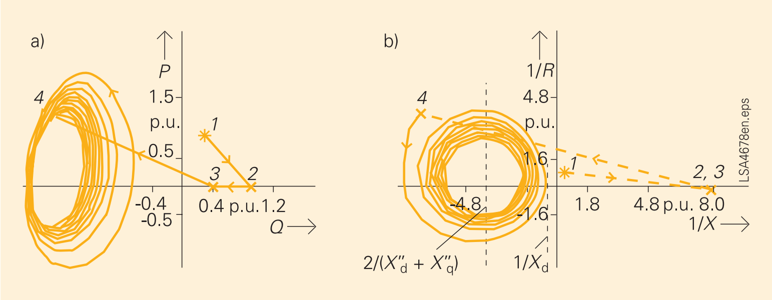


Fig. 5 Circle diagram profile of the admittance due to a three-pole short circuit lasting 0.2 s (9.88 MVA motor)
a) Power circle diagrams
b) Admittance circle diagrams
1 – Initial value
2 – Value at the start of the short-circuit
3 – Value on short-circuit tripping
4 – value after short-circuit tripping

2.3 Undervoltage protection

Besides the protection of equipment in the face of electrical faults, disturbances or disruptions, the protection engineer's task also encompasses the consideration of system operating states or actions by operating personnel that ought not to occur at all if the applicable work instructions (safe isolation, earthing, etc.) are complied with exactly. In extreme exceptional circumstances such as the coincidence of several disturbances in a system, an operating error can never be ruled out entirely, be it due to a stress situation or because such complex disturbances have not yet been described in the operating manual. When such disturbances occur, it is the task of the protection engineer – conscious of his responsibility – to employ suitable measurement methods and automated switching and control commands, so as to counteract a risk for persons or to protect equipment against damage.

Undervoltage protection is an example of this. If the upstream feed to a supply busbar is deactivated, the motors fed by it do not receive a voltage and stop. Undervoltage protection detects that the motor does not have a voltage and opens the circuit-breaker directly assigned to it. This ensures that, if the supply should suddenly return, the motor will not unexpectedly be connected to a voltage, which might possibly endanger service personnel.

Moreover, commissioning of a drive system with several motors powered from one busbar generally requires sequential startup of the individual motors. In many cases, simultaneous startup of several motors will overload the infeed due to the sum of the starting currents, which will lead to renewed pickup of a protection facility, e.g. the overload protection for the feeding transformer. Here also, the undervoltage protection at each motor feeder performs the task of setting the overall system to a defined basic state out of which operating personnel can successively start up the drive units again.

A further task of undervoltage protection is to protect a motor against damage that might arise from inadmissible starting when the voltage returns. This applies in particular to motors that have to be started up via star-delta changeover. In practice, a setting of 40 % of the rated voltage has proven suitable for detecting power failure and opening the circuit-breaker. The tripping delay must be coordinated with the loss of synchronism protection. If the power system voltage should drop only briefly, the motor can often continue to run after the voltage returns. Therefore an undervoltage protection tripping delay of about 1 to 2 seconds is adequate.

■ Summary

Large synchronous motors perform important tasks, that are sometimes relevant to safety, in an production process. The purpose of electrical protection is to safeguard these motors against damage to the best extent possible or to limit the extent of occurring damage as far as possible. Strict selectivity of the protection facility is just as important. This means that a motor should remain in operation for as long as its specified operating parameters permit.

The 7UM62 numerical protection relay meets both requirements excellently. Electrical faults and inadmissible operating states are reliably detected and remedied. The protection functions' pickup characteristics are adapted to the motors' operating characteristics, thus achieving high motor drive availability.

Synchronization and Protection of Synchronous Motors with the 7UM62

Use of the 7UM62 as a control and protection unit for synchronous motors is described in the application example. At the premises of the customer Petrobras (Brazil), the protection equipment was to be renewed and, furthermore, the problem of synchronization of the motor after startup had to be resolved. This article focuses on describing the implemented synchronization solution, i.e. the controlled connection of static excitation.

■ 1. Introduction

Synchronous motors are frequently started as asynchronous motors and the excitation is connected shortly before the synchronous speed is reached. Differing technical solutions can achieve this. In most cases, the excitation package provided includes such a control facility. This is also the case with Siemens whenever a turnkey solution (motor plus excitation) is delivered. After closing of the circuit-breaker by the controller (often a SIMATIC), decay of the starting current is checked. In parallel, the speed is monitored via an external sensor. Excitation is connected once the starting current has dropped to below 120 % of the rated motor current and the speed is higher than 96 % of the synchronous speed.

There were no speed sensors in the specific application discussed. However, there was access to the sliprings and the rotor frequency could be derived via the voltage induced in the rotor, thus making it possible to indirectly derive the speed. The motor has reached the synchronous speed if the voltage is zero.

Now, the rotor begins to turn when the motor is activated. The measured frequency of the rotor voltage is proportional to the slip. The frequency of the stator's rotation field is measured when the rotor is at standstill (s = 1). Continuous acceleration of the rotor leads to a reduction in the slip and thus to a drop in the frequency measured in the rotor's voltage. The amplitude of the induced voltage also drops at the same time. The excitation circuit-breaker must be closed shortly before the synchronous speed is reached and the motor then pulls itself into synchronism. What is important in this technical solution is determining of the exact moment for connection of the excitation. Damage to the motor is risked if this takes place purely randomly.

Fig. 1 shows the course of the rotor voltage during starting of the motor. Clearly recognizable are the changing frequency, dropping of the voltage and approximation to the synchronous speed. The ideal connection point for closing of the exciter circuit-breaker (contactor) is when the slip between the stator and the rotor is 4 % to 3 % or less, which corresponds to a very low frequency.

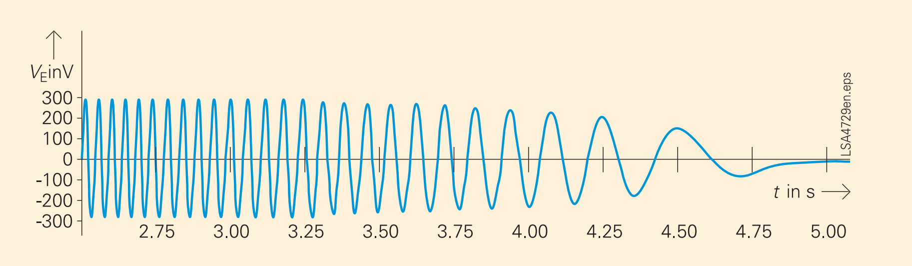


Fig. 1 Measured rotor voltage (induced field voltage)

2. Synchronization solution

2.1 Concept

Fig. 2 shows connection of the 7UM62. In the solution presented here, there were no current transformers at the star point on the motor and so differential protection was not used. There were also requirements stipulating additional monitoring of the excitation voltage, which took place via the measuring transducer inputs. The rotor frequency was recorded via a resistor network connected to two binary inputs. This was connected in parallel with the de-excitation resistor. The voltage input V_{in} was also connected there to record the course of the rotor voltage on the protection unit's fault record and to enable assessment of connection quality. The busbar voltage and the current of the core-balance current transformer were also processed.

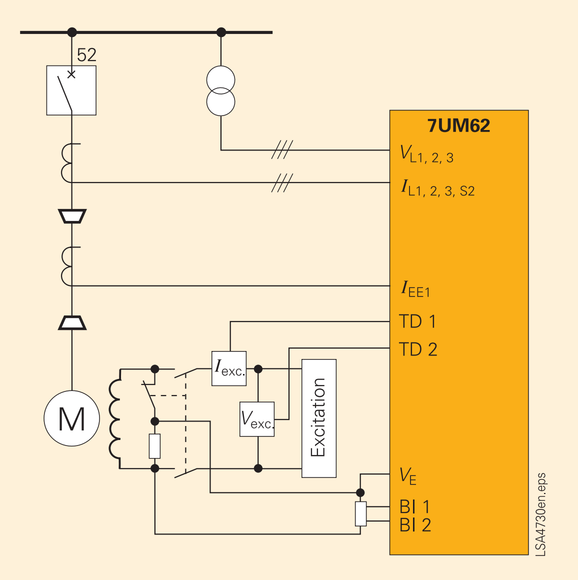


Fig. 2 Connection of the 7UM62

To determine the connection time, two binary inputs were used as the "sensor" whose logical signals were processed in an extensive PLC/CFC logic. Additional quantities such as

- Starting current and active power
- Interlocking depending on system conditions
- Slip between the rotor and stator as well as the closing command of power system circuit-breaker were also included in the logic or additionally monitored.

Fig. 3 shows sensing of the rotor voltage.

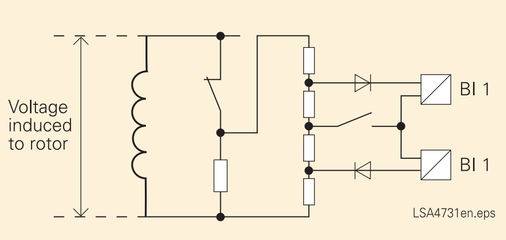


Fig. 3 Circuit for evaluating the rotor voltage

A voltage divider, to which the binary inputs are connected, was connected in parallel with the de-excitation resistor. Via a diode, a positive voltage, i.e. the positive half-wave of the rotor voltage, is fed to binary input (BI) 1 and, on the basis of the same principle, binary input 2 accordingly monitors the negative half-wave. The binary input threshold was set to 19 V so that the binary input picks up at an adequate voltage during one sinusoidal half-wave and drops out again if the voltage is below the threshold. The dropout threshold is slightly lower than the pickup threshold. During the measurements, the thresholds amounted to approximately 19 V (pickup 19.1 V and dropout 18.9 V).

2.2 Measurement method

Fig. 4 shows a zoomed section of the voltage induced in the rotor. Once the synchronous speed is approached, the frequency drops rapidly, which is also evident in the flatter increase of the AC voltage when it transits through zero.

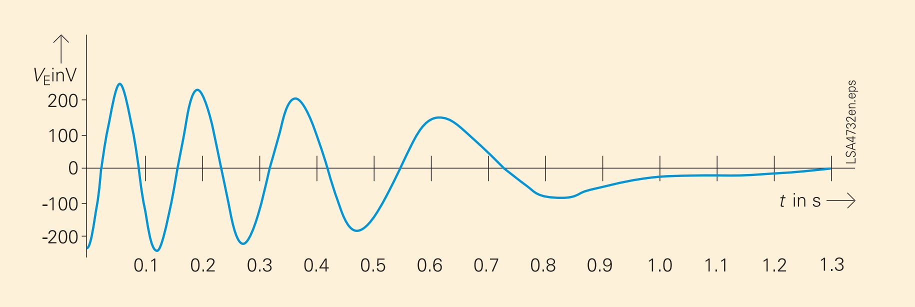


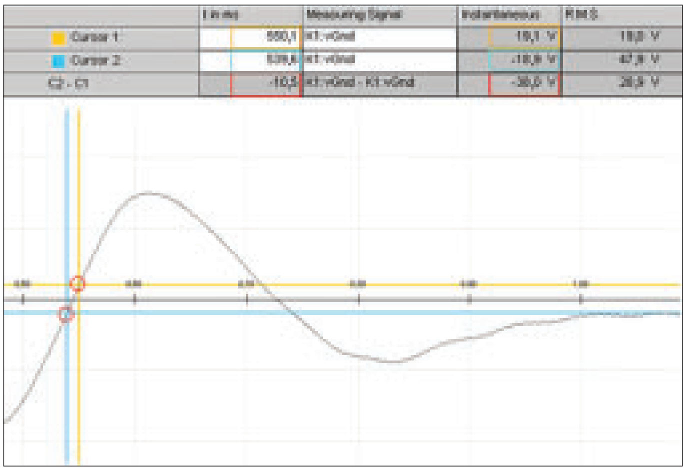
Fig. 4 Detailed view of Fig. 2

The timing of the signal change between zero transitions is monitored with the binary inputs. When a further enlargement of the rotor voltage is considered, Fig. 5 shows the trigger thresholds (ideal threshold of 19 V) with the cursors. In the event of a change from negative to positive, BI 2 will drop out and thus issue a "low" signal. BI 1 will pickup at an adequate voltage amplitude and will generate a "high" signal. Both signals are fed to a PLC/CFC logic, on the basis of which the voltage rate of change "d*V*/d*t*" is determined and monitored. The rotor frequency is therefore worked out indirectly.

The time difference determined on the basis of both trigger thresholds is around 10.5 ms if the thresholds are assumed to be at about 19 V. This time difference is of a magnitude comparable to the previous zero transition.

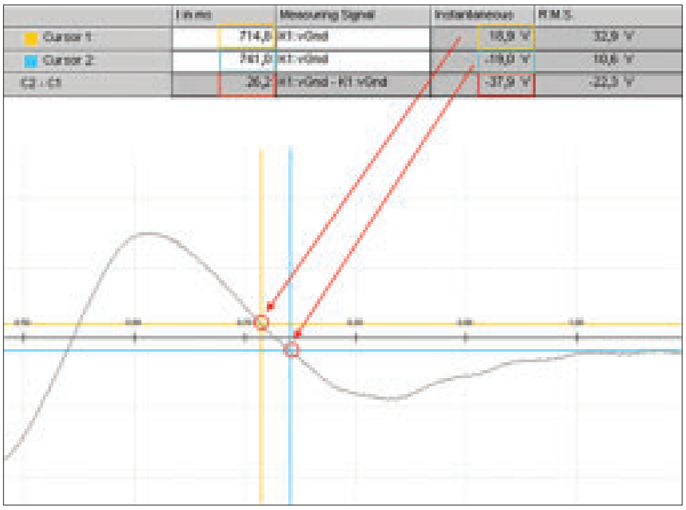
The logic is designed so that measurement of the zero transitions is begun after an adjustable time. This time must be determined during commissioning. It should be oriented to the decaying starting current. In the specific example, monitoring was started after 4 s. To this end, a timer was triggered after closing of the circuit-breaker via an auxiliary contact. After expiry of the time, the contact shown in Fig. 3 closes and the binary inputs are active. The times between the zero transitions can now be determined.

If the subsequent changes at the zero transitions (from positive to negative) are examined, it can be seen that the increase reduces clearly and a longer time difference is measured. According to Fig. 6, this time difference is 26.2 ms.



	t in ms	Measuring Signal	Instantaneous	RMS
🟨 Cursor 1	550,1	K1:vGnd	19,1 V	19,0 V
🟦 Cursor 2	539,6	K1:vGnd	-18,9 V	47,9 V
C2 - C1	-10,5	K1:vGnd - K1:vGnd	-38,0 V	28,9 V

Fig. 5 First measured passage through zero (BI1 is active and BI 2 is inactive)



	t in ms	Measuring Signal	Instantaneous	R.M.S.
🟨 Cursor 1	714,8	K1:vGnd	18,9 V	32,9 V
🟦 Cursor 2	741,0	K1:vGnd	-19,0 V	10,6 V
C2 - C1	26,2	K1:vGnd - K1:vGnd	-37,9 V	-22,3 V

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Fig. 6 Measurement of the next zero transition

The time difference measured is greater than in the previous measurement and in all other measurements since starting the motor. We can therefore conclude that slip is clearly reduced. The ideal time for closing the excitation circuit-breaker is approached. It is released when the time criterion (adequately flat rise in the rotor voltage) is met and a zero transition change has taken place. These principal conditions are processed in further logic blocks. Once all conditions are met, a CLOSE command is sent to the excitation circuit-breaker and the motor is synchronized.

Load connection is enabled by a further relay two seconds after applying of the excitation voltage (field voltage). General starting supervision also takes place, by means of which the starting and synchronization operations are aborted if not all conditions have been met within a certain time. In this specific case, this time was 8 seconds in duration. This time depends on the motor's starting time.

Numerous oscillographic recordings of motor starting operations were carried out to check the chosen solution. The stator current and the stator voltage and also the voltage induced in the rotor were analyzed. The recorded operations resulted in almost identical curves, as can be seen in Figs. 1 and 4.

The PLC/CFC logic was tested in detail with the records and logs.

“Live” commissioning on the motor then took place, which did not present any problems. All synchronous motors of the customer Petrobras were then equipped with this solution.

■ 3. Protection and additional functions used

The 7UM62 features the protection functions needed for motor applications. The protection functions used are listed below with their ANSI numbers.

• 27	Undervoltage protection
• 46	Negative-sequence (unbalanced-load) protection
• 47	Phase-sequence voltage
• 49	Stator thermal overload protection
• 50BF	Breaker failure protection
• 50G	Earth-fault protection (zero-sequence current)
• 50/51	Time-overcurrent protection
• 59	Overvoltage protection
• 81O/U	Overfrequency and underfrequency protection

Further protection/monitoring functions were realized by means of PLC/CFC. To this end, measured values were evaluated, including via the threshold monitoring function. In detail, these were:

• 55	Power factor protection
• 78(40)	Out-of-step protection of the synchronous motor (under-excitation protection can also be used to advantage here)
• 86	Lockout function/restart inhibit

- Monitoring of the excitation current and voltage
- Calculation of the rotor resistance on the basis of the excitation quantities
- Display of the excitation voltage and current and of the calculated rotor resistance
- Load connection

It also ought to be mentioned that the excitation current and voltage were recorded via sensors and these were linked to the relay's internal measuring transducers via the 4-20 mA interfaces. The calculated rotor resistance and the excitation voltage and current were provided as measured values on the display and can be shown via the selection menu for measurements on the 7UM62.

Loss of synchronism (out of step) of the synchronous motor is also supervised via power factor (cos φ) and excitation current monitoring.

■ Summary

The SIPROTEC 7UM62 features all necessary protection functions applied for motor protection. Further protection and monitoring functions were realized by means of PLC/CFC.

Appendix

■ *Siemens PTD EA on the Internet*

For product support in the use of SIPROTEC protection relays, the following information or documentation can be downloaded free of charge from our Internet page www.siprotec.de:

- Catalog sheets and documentation
- Updates and bug fixes for DIGSI
- Demo software and utilities
- Firmware updates
- Protocol updates

... and more

In this area you will find :

- Catalogue sheets and documentation
- Updates and bugfixes for DIGSI
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... and more

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