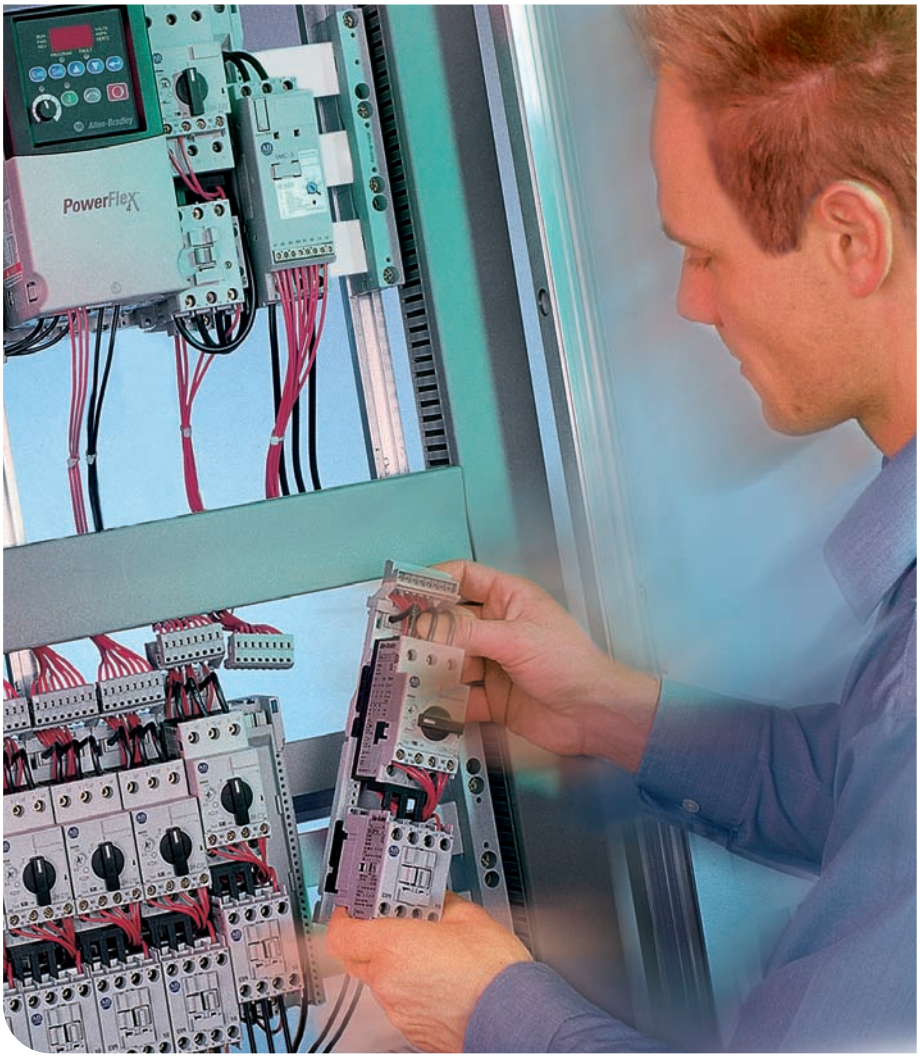
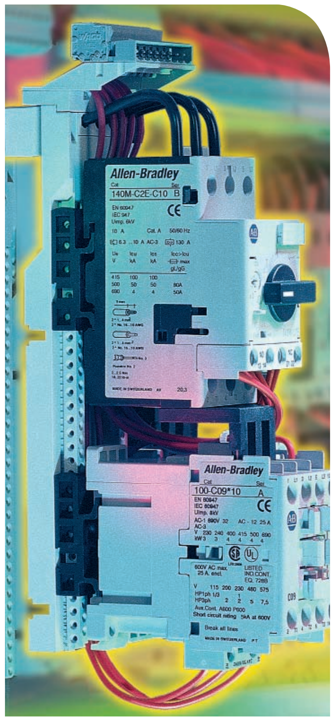
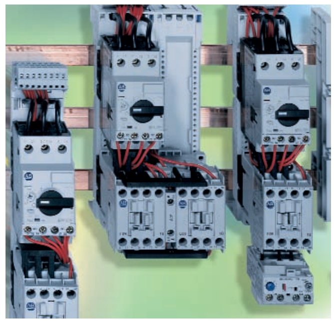
Allen-Bradley

Low-Voltage Switchgear and Controlgear

Technical Document







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Rockwell Automation would like to thank the authors of the present document and their assistants for their valuable contributions.

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General preliminary comments

The present technical manual is intended as an aid in project design and the application of low-voltage switchgear and controlgear in switchgear assemblies and machine control. The focus of the document is on electromechanical switchgear, however electronic devices used in low-voltage engineering have also been included. They are in many cases an effective alternative to mechanical devices.

The discussions relate – insofar relevant – to the IEC standards, which correspond to the European CENELEC standards. Where standards are quoted, the respective IEC designations are listed. The numbering of the CENELEC standards (EN) largely corresponds to that of the IEC standards. National standards (e.g. DIN/VDE or BS) in some cases have differing numbering for historical reasons, but in terms of content are largely identical to the IEC and EN standards, apart from rare national deviations. In relation to the requirements of other standard zones, especially in North America, reference is made to specific publications. The physical characteristics are generally applicable.

For switchgear combinations the standard IEC 60439-1 is referred to that is in effect at issuance of this document. It is expected that IEC 61439-1 will shortly replace IEC 60439-1. The statements in the present documentation for switchgear assemblies also apply for IEC 61439-1.

Statements made in this document concentrate on the underlying principles and facts and avoid – insofar as this is possible – stating technical data relating to specific products in order to avoid premature obsolescence of the information contained. The applicable technical data about the products should be obtained from the latest valid product documentation as published in printed and “electronic” catalogs and electronic documentation like RALVET.

0 Table of contents

1 Load characteristics and utilization categories

The characteristics of the load to be switched or controlled determine the loading of the switchgear and correct selection of the latter for the respective application. In particular the loading of contacts by current and voltage when circuits are made and broken is of high significance. Thus the making and breaking current under resistance load corresponds to the continuous operational current while for example squirrel-cage induction motors draw a multiple of the rated operational current when they are switched on and accelerate.

1.1 Utilization categories simplify the selection of devices

In order to make the choice of devices easier, utilization categories are defined in the standards for low-voltage switchgear (IEC 60947-1, -2, -3, -4, -5, -6) that take into account the intended application and hence the associated loading of the various low-voltage switchgear types, such as contactors, disconnectors, circuit breakers and load switches (**Tab. 1.1-1**). The rated operational currents or rated operational powers are listed in the technical data for the devices – usually for various rated operational voltages. For the sake of universal applicability the data is usually stated for several utilization categories for one and the same piece of switchgear. For project engineers, the selection of devices is basically reduced to the comparison of performance data of the switchgear for the respective utilization category with the ratings of the load and the choice of a device which meets or exceeds the ratings of the load.

When the rated operational voltage U_e and the rated operational current I_e are stated for a certain utilization category, the required making and breaking capacity for the item of switchgear is defined. Thus in general no further agreements between users and manufacturers are required. The selection of a suitable device and comparison of products is thus facilitated.

The test regulations in the IEC standards define the test parameters for the individual utilization categories. Manufacturers are obliged to carry out tests according to these standards. This ensures the suitability of the tested devices for the respective application and frees the user from getting “bogged down” in technical details.

The conditions for application in practice may differ considerably – in a favorable as well as adverse sense – from these standardized conditions. Examples are heavy-duty starting, high frequency of operation, especially long equipment life span. In such cases, the users and manufacturers must agree the permitted loads. In the catalogs as well as in the RALVET electronic documentation, the corresponding performance data are stated for the most common special applications.

Because of the very high and cost-intensive expenditures for testing, data for the most important and common utilization categories are usually provided. In cases going over and beyond this consultation is required.

Nature of current	Category	Typical applications	Relevant IEC product standard
a.c.	AC-20A, AC-20B AC-21A, AC-21-B AC-22A, AC-22B AC-23A, AC-23B 3)	Connecting and disconnecting under no-load conditions Switching of resistive loads, including moderate overloads Switching of mixed resistive and inductive loads, including moderate overloads Switching of motor loads or other highly inductive loads	60947-3
	AC-1 AC-2 AC-3 AC-4 AC-5a AC-5b AC-6a AC-6b AC-7a AC-7b AC-8a AC-8b	Non-inductive or slightly inductive loads, resistance furnaces Slip-ring motors: starting, switching off Squirrel-cage motors: starting, switching off motors during running Squirrel-cage motors: starting, plugging1), inching2) Switching of electric discharge lamp controls Switching of incandescent lamps Switching of transformers Switching of capacitor banks Slightly inductive loads in household appliances and similar applications Motor-loads for household applications Hermetic refrigerant compressor motor control with manual resetting of overload releases Hermetic refrigerant compressor motor control with automatic resetting of overload releases	60947-4-1
	AC-52a AC-52b AC-53a AC-53b AC-58a AC-58b	Control of slip ring motor stators: 8 h duty with on-load currents for start, acceleration, run Control of slip ring motor stators: intermittent duty Control of squirrel-cage motors: 8 h duty with on-load currents for start, acceleration, run Control of squirrel-cage motors: intermittent duty Control of hermetic refrigerant compressor motors with automatic resetting of overload releases: 8 h duty with on-load currents for start, acceleration, run Control of hermetic refrigerant compressor motors with automatic resetting of overload releases: intermittent duty	60947-4-2
	AC-51 AC-55a AC-55b AC-56a AC-56b	Non-inductive or slightly inductive loads, resistance furnaces Switching of electric discharge lamp controls Switching of incandescent lamps Switching of transformers Switching of capacitor banks	60947-4-3
	AC-12 AC-13 AC-14 AC-15	Control of resistive loads and solid-state loads with isolation by optocouplers Control of solid-state loads with transformer isolation Control of small electromagnetic loads Control of a.c. electromagnetic loads	60947-5-1
	AC-12 AC-140	Control of resistive loads and solid state loads with optical isolation Control of small electromagnetic loads with holding (closed) current ≤ 0,2 A, e.g. contactor relays	60947-5-2
	AC-31A, AC-31B AC-33A, AC-33B AC-35A, AC-35B AC-36A, AC-36B 3)	Non inductive or slightly inductive loads Motor loads or mixed loads including motors, resistive loads and up to 30 % incandescent lamp loads Electric discharge lamp loads Incandescent lamp loads	60947-6-1

Nature of current	Category	Typical applications	Relevant IEC product standard
a.c.	AC-40 AC-41 AC-42 AC-43 AC-44 AC-45a AC-45b	Distribution circuits comprising mixed resistive and reactive loads having a resultant inductive reactance Non-inductive or slightly inductive loads, resistance furnaces Slip-ring motors; starting, switching off Squirrel-cage motors: starting, switching off motors during running Squirrel-cage motors: starting, plugging1), inching2) Switching of electric discharge lamp controls Switching of incandescent lamps	60947-6-2
	AC-7a AC-7b	Slightly inductive loads for household appliances and similar applications Motor-loads for household applications	61095
a.c. and d.c.	A B	Protection of circuits, with no rated short-time withstand current Protection of circuits, with a rated short-time withstand current	60947-2
	DC-20A, DC-20B DC-21A, DC21B DC-22A, DC22B DC-23A, DC23B 3)	Connecting and disconnecting under no-load conditions Switching of resistive loads, including moderate overloads Switching of mixed resistive and inductive loads, including moderate overloads (e.g. shunt motors) Switching of highly inductive loads (e.g. series motors)	60947-3
d.c.	DC-1 DC-3 DC-5 DC-6	Non-inductive or slightly inductive loads, resistance furnaces Shunt-motors, starting, plugging1), inching2). Dynamic breaking of motors Series-motors, starting, plugging1), inching2). Dynamic breaking of motors Switching of incandescent lamps	60947-4-1
	DC-12 DC-13 DC-14	Control of resistive loads and solid-state loads with isolation by optocouplers Control of electromagnets Control of electromagnetic loads having economy resistors in circuit	60947-5-1
	DC-12 DC-13	Control of resistive loads and solid state loads with optical isolation Control of electromagnets	60947-5-2
	DC-31 DC-33 DC-36	Resistive loads Motor loads or mixed loads including motors Incandescent lamp loads	60947-6-1
	DC-40 DC-41 DC43 DC-45 DC-46	Distribution circuits comprising mixed resistive and reactive loads having a resultant inductive reactance Non-inductive or slightly inductive loads, resistance furnaces Shunt-motors: starting, plugging1), inching2). Dynamic breaking of d.c. motors Series-motors: starting, plugging1), inching2). Dynamic breaking of d.c. motors Switching of incandescent lamps	60947-6-2
1) By plugging is understood stopping or reversing the motor rapidly by reversing motor primary connections while the motor is running. 2) By inching (jogging) is understood energizing a motor once or repeatedly for short periods to obtain small movements of the driven mechanism. 3) The utilization categories with annex A apply for frequent operations, those with annex B for infrequent/occasional operations			

Tab. 1.1-1
Examples of utilization categories for low-voltage switchgear as per IEC 60947-1 ed. 5.0 Appendix A. Copyright © 2007 IEC, Geneva, Switzerland. www.iec.ch

1.2 Electrical heating devices

Electrical heating devices are for example used for heating rooms, industrial resistance furnaces and air-conditioning plants.

In the case of wound resistance elements, the making current can be 1.4 times the rated current. In the selection of switchgear devices it should be noted with respect to the rated operational current that (in contrast to the motor) the current consumption increases when the mains voltage increases. When contactors are used, utilization category AC-1 should be used as a basis for alternating current and DC-1 for direct current. For manual switching, a load-switch with corresponding load-switching capacity (AC-21) is sufficient.

Furthermore, if the ambient temperature is very high this must be taken into account.

Heating circuits are often single pole circuits. Usually multi-pole switchgear devices with poles connected in parallel are used, which enables to increase the permissible load current. For the load-carrying capacity of switchgear units with poles connected in parallel, see section **2.4.1.1**.

1.3 Lamps and illumination equipment

The illumination devices are subject to constant change due to developments in energy efficiency and electronics. For the choice of associated switching (e.g. contactors) and protective equipment (e.g. miniature circuit breakers and circuit breakers) not only the type of lighting equipment itself should be taken into account but also the kind of control circuit. Particular attention should be paid to inrush currents caused by compensation capacitors and charging of electronic control devices. This loading may be reduced by the attenuating effect of long lines.

The startup and operational current loads should be obtained from the respective manufacturers. The below descriptions relate to the basic characteristics. Also see **Tab. 1.3-1**.

In general it is recommended to utilize a max. of 90 % of the current capacity of the switchgear as the current consumption of lighting equipment typically increases when the voltage increases.

1.3.1 Incandescent lamps

The filaments of incandescent lamps have a very low ohmic resistance when cold. This creates a high current peak when they are switched on (up to $15 \cdot I_e$). The making capacity of the switchgear must thus at least correspond to this value (utilization category AC-5b). Upon switching off, only the rated current has to be disconnected due to the high resistance of the hot filaments.

1.3.1.1 Halogen lamps

Halogen lamps are actually a version of incandescent lamps and their behavior is basically the same as the latter. The lamps are often designed for low voltages and powered via a transformer or electronic mains adapter. Their inrush currents should be taken into account for switching on.

1.3.2 Discharge lamps

Discharge lamps such as fluorescent tubes, energy saving lamps, mercury vapor lamps, halogen metal vapor lamps or sodium vapor lamps require both a starting circuit and a current limitation device. These devices may be conventional or electronic. Discharge lamps with electromagnetic series chokes have a low power factor and are therefore usually compensated. The compensation capacitance leads to high inrush currents that must be taken into account when the switchgear is selected.

Most electronic series devices have a high power factor (e.g. $\cos\varphi \approx 0.95$), nevertheless during switching on there occurs a charging current surge that loads the switchgear accordingly.

When selecting the switchgear for high in-rush currents, the permitted rated power for the switching of capacitors should be taken into account as per utilization category AC-6b. In order to prevent undesired release of miniature circuit breakers with the simultaneous activation of a number of fluorescent tubes, information is provided by the tube manufacturers on the maximum number of luminescent tubes (including series devices) that can be operated via a single protective switch.

Lamp type, (switch)	**Making current peaks**	**Startup time [min]**	**Starting current**	**cos φ**	**Calculation basis for I_e**
Incandescent lamps	$15 \cdot I_e$	-	-	1	$\leq I_{eAC-5b}$
Halogen lamps - Transformer operation - ECG[1] operation	 $10 \cdot I_e$	 -	 -	 0.95	 see Section1.4 $\leq 0.7 \cdot I_{eAC-3}$
Luminescent lamps (choke operation) - uncompensated - parallel compensated - DUO circuit	 $\approx 2 \cdot I_e$ $\approx 20 \cdot I_e$ $\approx 2 \cdot I_e$	 - - -	 - - -	 0.5 0.9 0.9	 $\leq I_{eAC-5a}$ $\leq I_{eAC-1}$, $\leq I_{eAC-6b}$ $\leq I_{eAC-1}$
Luminescent lamps - ECG[1]) operation, AC	 $10 \cdot I_e$	 -	 -	 0.9	 $\leq 0.7 \cdot I_{eAC-3}$
Mercury vapor high pressure lamps - uncompensated - parallel-compensated	 $\approx 2 \cdot I_e$ $\approx 20 \cdot I_e$	 3 – 5 3 – 5	 $\approx 2 \cdot I_e$ $\approx 2 \cdot I_e$	 0.4 – 0.6 0.9	 $\leq 0.5 \cdot I_{eAC-1}$ $\leq 0.5 \cdot I_{eAC-1}$, $\leq I_{eAC-6b}$
Halogen metal vapor lamps - uncompensated - parallel-compensated	 $\approx 2 \cdot I_e$ $\approx 20 \cdot I_e$	 5 – 10 5 – 10	 $\approx 2 \cdot I_e$ $\approx 2 \cdot I_e$	 0.4 – 0.5 0.9	 $\leq 0.5 \cdot I_{eAC-1}$ $\leq 0.5 \cdot I_{eAC-1}$, $\leq I_{eAC-6b}$
Sodium vapor high pressure lamps - uncompensated - parallel-compensated	 $\approx 2 \cdot I_e$ $\approx 20 \cdot I_e$	 5 – 10 5 – 10	 $\approx 2 \cdot I_e$ $\approx 2 \cdot I_e$	 0.4 – 0.5 0.9	 $\leq 0.5 \cdot I_{eAC-1}$ $\leq 0.5 \cdot I_{eAC-1}$, $\leq I_{eAC-6b}$
Dual-source lamps	$\approx 1.3 \cdot I_e$	≈ 3	$\approx 1.3 \cdot I_e$	1	$\leq 0.9 \cdot I_{eAC-1}$

Tab. 1.3-1
Making currents for lamps and notes on selecting switchgear
[1]*) ECG … Electronic control gear*

1.4 Transformers

If a low-voltage transformer is switched on, there is a short-term current surge (rush). The peak surge currents evoked by field set-up can be up to 30 times greater than the transformer rated current. The inrush currents vary according to the transformer type. They depend on the position of the coil, the characteristics of the magnetic circuit and especially on the phase angle of the voltage during switching on. The switchgear must have a correspondingly high making capacity in order to avoid contact welding.

IEC 60947-4-1 provides the utilization category AC-6a for switching transformers. The permitted rated operational current I_{eT} (AC-6a) for switching transformers with a making rush factor of ≤ 30 can be determined as per IEC 60947-4-1 (Tab.7b) from the data of the AC-3 switching capacity:

$I_{eT30} = 0.45 \cdot I_{eAC-3}$

for $n \leq 30$
n = peak value of the making current/peak value of the rated operational current

In the case of larger rush factors the following applies:

$I_{eTn} = I_{eT30} \cdot 30/n$

The factor «n» should be specified by the transformer supplier. If no specifications are available, the following guideline values apply for «n»:

Transformers up to approx. 1 kVA	at 230 V	n ≈ 20
	at 400 V	n ≈ 15
larger transformers	at 400 V	n ≈ 15 ... 30

Note
The thermal continuous current $I_{th(e)}$ may not be exceeded.

Transformers in welding machines are usually designed so that inrush current peaks and the short-circuit current with electrodes short-circuited are limited (n ≈ 10). The contactor is selected for switching these currents operationally.

If the individual welding current surges are not switched by power semiconductors but by the primary contactor, this means that the latter has a high switching frequency and a very high number of operations. It is essential that the contactor selected is checked with respect to the permitted frequency of operation and the electrical life span. For the electrical endurance the selection can be based on approx. 70 % of the AC-1-ratings as long as the inrush currents are limited.

1.5 Reactive power compensation and switching of capacitors

1.5.1 Reactive power compensation

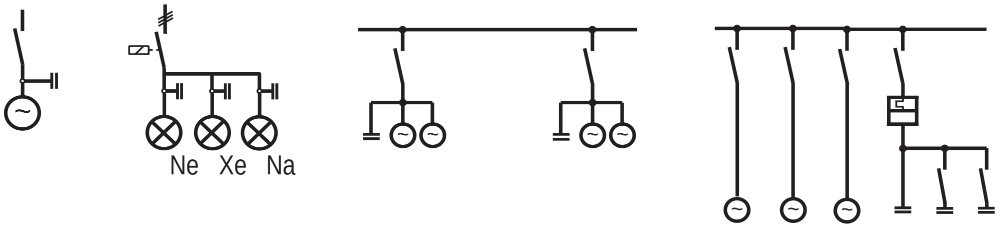
In electrical networks in which inductive consumers (e.g. motors) are switched on and off, the power factor cos φ often changes with each switching operation. The Power Utilities demand from their consumers that the ratio of the consumed effective power *P* to the drawn apparent power *S* does not fall below a certain value, as the transmission of apparent power is uneconomic.

The reactive power of motors, luminescent lamps with series chokes and other inductive loads is therefore frequently compensated by connecting capacitors, in order to reduce the additional load of transformers and lines by the reactive current.

In deciding whether it is more advantageous to compensate individual consumers with fixed capacitors or to provide central compensation units, economic and technical considerations are definitive. Control units for central compensation have a higher price per power unit (kVA). If allowance is made however for the fact that in most operations not all consumers are switched on at the same time, a lower installed capacitor power is often sufficient for central compensation.

1.5.1.1 Individual compensation

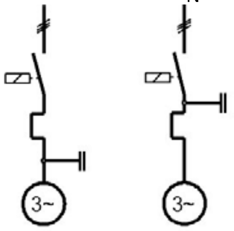
For individual compensation (**Fig. 1.5-1** a) the capacitors are directly connected to the terminals of the individual consumer (e.g. motor, transformer, induction heater, luminescent lamp) and switched together with these via a common switchgear unit. Single compensation is recommended with large consumers with constant power consumption and long ON-times. They offer the advantage that the lines to the consumers are also relieved of load. The capacitors can frequently be connected directly to the terminals of the individual consumer and be switched on and off with a common switchgear device.



a) Individual compensation b) Group compensation c) Central compensation

Fig. 1.5-1
Compensation types

In the case of motors, the capacitors can be connected up- or downstream the motor protection unit (**Fig. 1.5-2**). In most cases the capacitor will be connected parallel to the motor (case 1). In this case the motor protection unit should be set to a smaller setting current I_e than the motor rated current I_N as the magnitude of the line current falls due to the compensation:



Case 1 Case 2

Fig. 1.5-2
Individual compensation of motors
$I_e = (\cos \varphi_1/\cos \varphi_2) \cdot I_N$
cos φ_1 *= power factor of the uncompensated motor*
cos φ_2 *= power factor of the compensated motor*

1.5.1.2 Group compensation

For group compensation each compensation device is assigned to one consumer group. This may consist of motors or also for example of luminescent lamps that are connected to the mains via a contactor or a circuit breaker (**Fig. 1.5-1** b).

1.5.1.3 Central compensation

Mostly reactive power control units are used for central compensation which are directly assigned to a main- or sub-distribution station (**Fig. 1.5-1** c). This is especially advantageous if many consumers with differing power requirements and variable on-times are installed in the network.

Central compensation also offers the advantage that

- the compensation device is easy to monitor due its central location,
- any retrospective installation or extension is relatively simple,
- the capacitive power is continuously adapted to the reactive power requirement of the consumers and
- making allowance for a simultaneity factor a lower capacitance is often required than for individual compensation.

See IEC 61921; Power capacitors – Capacitor batteries for correcting the low-voltage power factor

1.5.2 Switching of capacitors

Capacitors form oscillator circuits together with the inductances of the lines and the transformers. During closing, very high transient currents with higher frequencies may flow. Typical values are 10 ... 30 times the capacitor rated current at frequencies of 2 ... 6 kHz. For this reason, the switching of capacitors represents a very heavy load on switchgear and can result in increased contact burn-off or under adverse conditions even welding of the contacts. Especially when capacitors are switched by contactors, it should be ensured that they are discharged before switching-on to avoid even higher transient currents and welding of the contacts in case of adverse phase angles.

A harmonic component in the supply voltage leads to increased current consumption by the capacitors and results in additional heating of the current carrying circuits. To prevent any undesired temperature rise, the rated operational current of the contactors, load switches and circuit breakers shall be higher than the capacitor rated current. Generally this should only be 70 … 75 % of the rated current of the circuit breaker.

Taking into account the aforementioned facts, the switchgear should be dimensioned so that

- it does not weld at the high making currents and
- that no unacceptable temperature rise occurs during continuous duty.

1.5.2.1 Switching-on single capacitors

If a capacitor with a specific capacity is connected to the power supply, then the making current is largely determined by the transformer size and by the network impedance to the capacitors, i.e. from the prospective short-circuit current at the installation site of the capacitor.

The loading of the switchgear increases as

- the capacitance of the capacitors increases,
- as the rated power of the supplying transformer increases and hence its short-circuit impedance decreases,
- decreasing impedance of the connecting lines.

Table 7 in IEC 60947-4-1 states the below derivation of capacitor switching capacity $I_{eAC\text{-}6b}$ from the rated operational current $I_{eAC\text{-}3}$ in relation to the prospective short-circuit current i_k:

$$I_{e(AC-6b)} = i_k \cdot \frac{x^2}{(x-1)^2}$$

at

$$x = 13.3 \cdot \frac{I_{e(AC-3)}}{i_k}$$

valid for

$$i_k > 205 \cdot I_{e(AC-3)}$$

1.5.2.2 Switching of long, screened lines

Long screened lines have comparatively large capacitances and therefore create high transient current loads during switching. Typical applications are variable frequency drives. The peak currents to be expected should be taken into account when selecting switchgear to the same extent as for the switching of single capacitors.

1.5.2.3 Switching capacitors of central compensation units

If individual capacitors of capacitor banks are switched – for example in reactive power control units - especially adverse conditions occur at closing of the switchgear contacts as the capacitors already connected to the power supply represent an additional source of energy.

The inrush current is limited by the impedance of the circuit (conductors, capacitor inductance, inductances between the individual capacitor branches).

The loading of the switchgear is therefore determined by

- the power ratio of the switched capacitors to those already connected to the power supply and
- the impedance of the individual circuit branches

For avoiding welding of the switching contacts of the contactors the switchable capacitance can e.g. be increased, by additional inductances in the capacitor branches (e.g. a few winding turns of the connecting wires).

With special capacitor-contactors or capacitor-contactor-combinations that connect capacitances to the power supply via pre-charging resistances, a very high switchable capacitance at a minimum of interference with the supplying network can be achieved, as the making currents are specifically limited by the resistances and strongly reduced.

AC-6b is defined in IEC 60947-4-1 as the utilization category for the switching of capacitor banks.

1.6 Control circuits, semiconductor load and electromagnetic load

Regarding the specific aspects of the switching of control circuits, also refer to Section 5.

The utilization categories AC-12 to AC-15 for alternating current and DC-12 to DC-14 for direct current (see **Tab. 1.1-1**) make allowance for the specific loading of switchgear for switching of control circuits with semi-conductors or electromagnetic loads. When electromagnets are switched, for example contactor coils, particular attention is paid to the increased making load because of the pull-in current of the magnets and the increased breaking load due to the high inductance of the closed magnets.

In addition to the switching capacity of the contact in the sense of a maximum permitted load, very often the key criterion in the switching of control circuits is contact reliability, i.e. the capability of a contact or a chain of contacts to reliably switch small signals. This is especially the case for contacts in circuits of electronic controllers and in the signal range of ≤ 24 V / ≤ 20 mA (also see section **5.3.5**).

1.7 Three-phase asynchronous motors

The three-phase asynchronous motor – also known as the induction motor – is the most frequently used motor type for industrial drives. Especially in the form of a squirrel-cage induction motor, it dominates the field of industrial electrical drive technology.

1.7.1 Principle of operation

The key functional elements of the three-phase asynchronous motor (see **Fig. 1.7-1**) are the fixed stator with a three-phase coil supplied by the three-phase supply network and the revolving rotor. There is no electrical connection between the stator and rotor. The currents in the rotor are induced by the stator across the air-gap. The stator and rotor are composed of highly magnetizable dynamo plates with low eddy current and hysteresis losses.

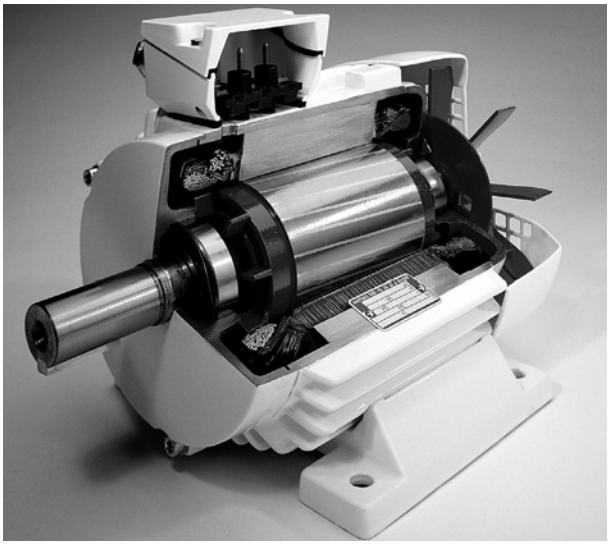


Fig. 1.7-1
Sectional view of a squirrel-cage three-phase motor with enclosed design

When the stator coil is connected to the power supply, the current initially magnetizes the laminated metal body. This magnetizing current generates a field that rotates with the synchronous speed n_s.

n_s = $60 \cdot f/p$
n_s = synchronous speed in min^{-1}
f = frequency in s^{-1}
p = pole pair number (pole number/2)

For the smallest pole number of $2p = 2$, with a 50 Hz power supply, the synchronous speed is $n_s = 3000\ \text{min}^{-1}$. For synchronous speeds with other pole numbers and for 50 and 60-Hz power supplies, see **Tab. 1.7-1.**

Pole number	2	4	6	8	10	12	16	24	32	48
$n_{s\ 50\ Hz}$	3000	1500	1000	750	600	500	375	250	188	125
$n_{s\ 60\ Hz}$	3600	1800	1200	900	720	600	450	300	225	150

Tab. 1.7-1
Synchronous speeds for 50 and 60 Hz power supplies

The rotating field of the stator induces a voltage in the coil of the rotor, which in turn creates a current flow therein. With the interaction of the rotating field of the stator with the conductors in the rotor through which a current flows, a torque is created in the direction of the rotating field.

The speed of the rotor is always smaller than the synchronous speed by the so-called slip *s*.

$s = (n_s - n)/n_s$
s slip
n_s synchronous speed
n operational speed

It is only because of this speed differential that a voltage can be induced in the rotor and hence the rotor current that is the prerequisite for the generation of the motor-torque. The slip increases with the load torque. Its rated value at the rated load of the motor depends on the rotor resistance and hence on the energy efficiency of the motor.

The torque curve of the induction motor is characterized by the breakdown-torque. This means that the torque of the motor increases with increasing speed to a maximum value and then rapidly falls back to zero at the synchronous speed. If the mechanical load of a motor running at normal service is increased beyond the value of the breakdown torque, it will stall, i.e. it comes to a halt. The magnitude of the breakdown torque is determined by the electrical reactance of the motor and hence by the motor's design. The slip that occurs at breakdown torque can be influenced by the rotor resistance. This effect is exploited in slip-ring motors by switching on external resistors (**Fig. 1.7-2** and **Fig. 1.7-3**).

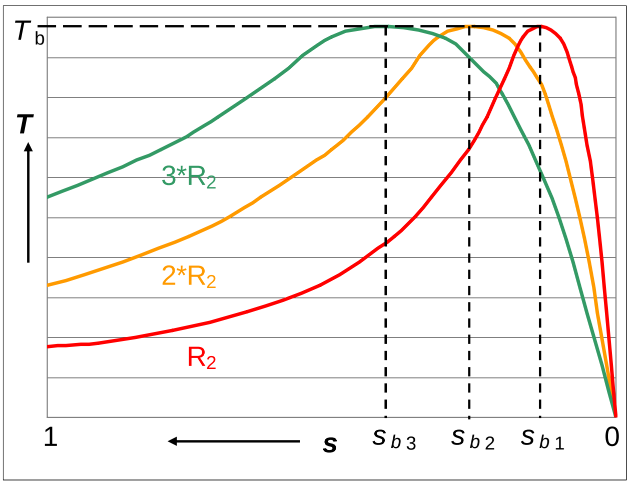


Fig. 1.7-2
The torque characteristic of asynchronous motors can quasi be extended by connecting resistors in the rotor circuit.
T_b *breakdown torque*
s *slip*
s_b *breakdown slip*
R_2 *rotor resistance*

Asynchronous motors behave electrically like transformers. The secondary winding is the rotor and the mechanical power output of the motor acts on the primary side like a – variable – load resistance. If no mechanical power output is produced at rest (on initiation of start-up), this load resistance is zero, i.e. the transformer is in effect secondarily shorted. This leads – depending on the rotor-internal resistance – to a high or very high current consumption of the motor during starting. In the case of slip-ring motors, the current consumption is reduced by connecting external resistors and hence the torque characteristic is adapted to the driven machine. With squirrel-cage induction motors (see section **1.7.1.2**) the current consumption and hence the torque characteristic are influenced by the design of the rotor cage.

1.7.1.1 Slip-ring motors

With slip-ring motors, the rotor winding is connected to slip rings and terminated with external resistances. The resistance of the external resistors influences the current flowing through the rotor and the speed-torque characteristic.

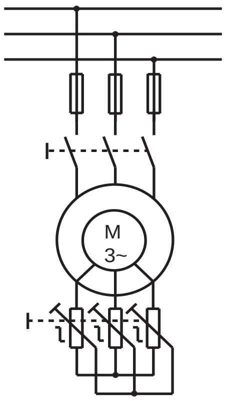


Fig. 1.7-3
Principal diagram of a slip-ring motor with external rotor resistances

Slip-ring motors represent the conventional method of controlling starting torque (and the current consumption) by selection of the rotor resistances. The highest attainable starting torque corresponds to the breakdown torque of the motor. This is independent of the magnitude of the rotor resistance. The primary current consumption of slip-ring motors is proportional to the rotor current. Thanks to these characteristics, slip-ring motors can achieve a high starting torque with relatively low current consumption.

The external resistors are usually changed in steps during motor startup. The rotor windings are shorted in normal continuous duty. By designing the rotor resistances for continuous duty, it is even possible to continuously influence the speed, albeit at the cost of high heat dissipation.

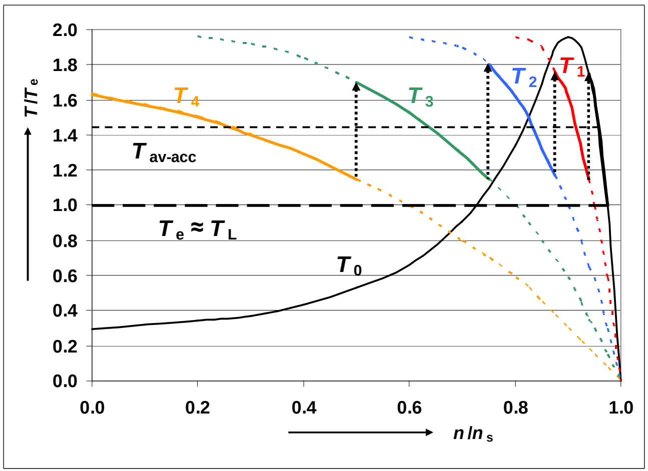


Fig. 1.7-4
Torque characteristic of a slip-ring motor with full-load start-up and stepped change of the rotor resistance during start-up

T_4 … T_1	motor torque with series-connected resistance stages ($R_4>R_3>R_2>R_1$)
T_0	motor torque with shorted rotor windings
$T_{av\text{-}acc}$	average starting torque
$T_e \approx T_L$	rated torque corresponds to load torque

1.7.1.2 Squirrel-cage induction motors

In the case of asynchronous machines with squirrel-cage induction rotors, the rotor consists of a grooved cylindrical laminated rotor package with rods of highly conductive metal (preferably aluminum), that is joined on the face side by rings to form a closed cage. The cage – at least in the case of small motors – is usually cast into the rotor.

To reduce the starting current and influence the starting torque characteristic, the coil rods are specially designed so that they create a high rotor resistance at rest and at low speeds by current displacement. They are usually placed crosswise at an angle to the axis of rotation to avoid variations in torque and to ensure smooth running characteristics.

Fig. 1.7-5 shows the typical characteristic of the torque and of the current in a cage induction motor in the speed range from rest to synchronous speed. Material and design form of the cage influence the shape of the characteristic curves.

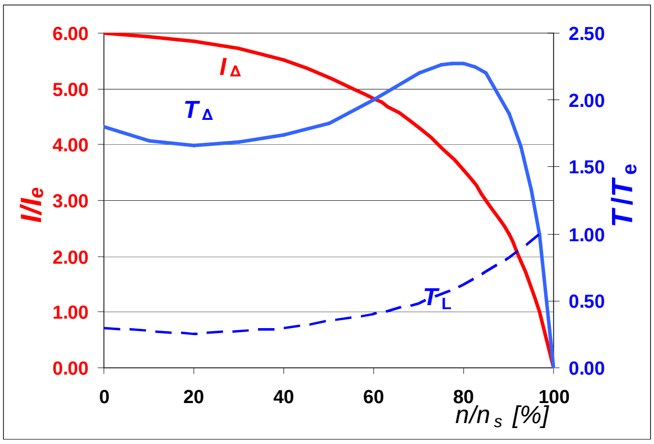


Fig. 1.7-5
Typical current and torque characteristic of a squirrel-cage induction motor between rest and synchronous speed.

I_Δ	*current characteristic with delta-connected windings*
T_Δ	*torque characteristic with delta-connected windings*
T_L	*load torque (example)*

The operating characteristics (**Fig. 1.7-6**) show that the asynchronous motor has a so-called "hard" speed characteristic, i.e. the speed changes only slightly with a change in loading. At low loading, the current consumption approaches the value of the idle running current, which is basically the same as the magnetization current of the motor.

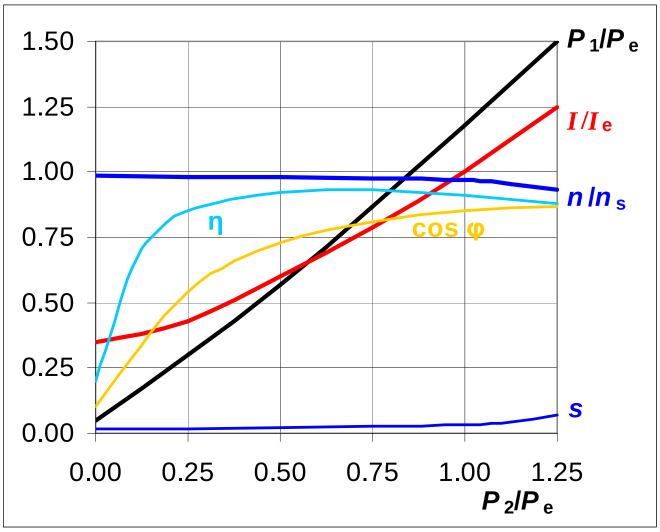


Fig. 1.7-6
Operating characteristics of an asynchronous motor as a function of load

n = speed
n_s = synchronous speed
s = slip
P_1 = power intake
P_2 = power output
P_e = rated operational power
η = efficiency
cos φ = power factor
I = current consumption
I_e = rated operational current

n The speed n only decreases slightly with increasing load. Normal squirrel-cage induction motors thus have "hard" speed characteristics.

s The slip s increases roughly proportionally with increasing load.

cos φ The power factor cos φ is strongly dependent on the load and only reaches its highest value in a state of overload. The power factor is relatively adverse in the part-load range, as the magnetization is practically constant.

η The efficiency η remains relatively constant and in the upper half-load range remains practically unchanged. It generally reaches its highest value below the rated operational power P_e.

I The current I increases proportionally from around the half-load mark. Below this point it falls less strongly and then goes over to the idle running current I_0 (constant magnetization)

P_1 Starting from the idle running consumption, the power intake P_1 increases roughly proportionately to the load. In the overload range, its rate of increase is somewhat higher as losses increase more strongly.

T The torque in the operating range is calculated as follows:

$$T = \frac{\sqrt{3} \cdot U \cdot I \cdot \cos\varphi \cdot \eta \cdot 9.55}{n} [Nm]$$

U voltage across the motor [V]
I current [A]
cos*φ* power factor
η efficiency of the motor
n speed [min^{-1}]

The rated operational currents, starting currents and the torque characteristic of cage induction motors depend, among other things, on their design, especially the material and form of the cage, as well as on the number of poles. The specifications provided by the motor manufacturer apply in each individual case. Typical values for motors can be obtained from the RALVET electronic documentation.

For switching asynchronous motors, under IEC 60947 the utilization categories AC-2 to AC-4 among others are defined to facilitate the user in the selection of suitable contactors (**Tab. 1.1-1**). These utilization categories make allowance for the loading of the switchgear by the increased making currents when stationary motors are switched on and for the fact that the effective switching voltage of a running motor is only around 17 % of the rated operational voltage because the running motor develops a back-e.m.f. (counter voltage to supply voltage).

1.7.1.2.1 High efficiency motors

In the context of the efforts of saving energy and pollution control, the efficiency of electric motors and drives has become an issue. This on the background of appr. 40% of the global electricity being used for operating electric motors. The IEC standard 60034-30 (2008) defines efficiency classes for general purpose induction motors of the power range of 0.75 …375 kW and with 2, 4 or 6 poles (**Tab. 1.7-2**). The term MEPS (Minimum Energy Performance Standard) is being used in this context [25]. It is expected that efficiency class IE2 shall become the minimum level for new motors in the area of the European Union, IE3 may be required in a further step (minimum requirements, if any, are subject of national legislation).

IEC Class	IEC Code	EFF Code 1)	NEMA
Super Premium Efficiency	IE4		
Premium Efficiency	IE3		NEMA Premium
High Efficiency	IE2	EFF1	EPAct
Standard Efficiency	IE1	EFF2	
Below stand Efficiency	‘---	EFF3	
1) CEMEP classification (CEMEP = European sector committee of Manufacturers of Electrical Machines)			

Tab. 1.7-2
Efficiency classes for general purpose induction motors according to IEC 60034-30 (2008) in comparison to the EFF-codes of CEMEP and the codes used by NEMA. IE4 is not yet defined and reserved for the future.

High efficiency motors that comply with the MEPS standard may have higher starting currents and cause higher transient current peaks upon switching. The starting torque may be comparatively lower for the same starting current, while the breakdown torque may be higher.

When selecting switchgear for starting high efficiency motors, attention should be paid to the selection of the proper release class of overload relays (start-up time could become longer at higher starting current levels). In case of using (current-limiting) circuit breakers the choice of breakers with high magnetic trip (c.b.'s for transformer protection) may be required for avoiding nuisance tripping due to high switching transients.

Above factors should particularly be considered in retrofit applications when replacing old standard motors with new high efficiency motors.

Also, if softstarters are used, the start current may be higher for a given start torque, so a check should be made to ensure the equipment is rated accordingly. The available start torque may also need to be evaluated to ensure matching to the load characteristics.

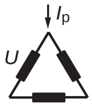
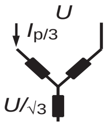
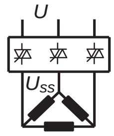
1.7.1.3 Influence of the voltage across the windings

In order to reduce the high current consumption of squirrel-cage induction motors on starting and the associated, often disruptive, power supply loading and to reduce the high starting torque when driving sensitive machines, a wide variety of methods is available that is based on the reduction of the voltage applied across the motor windings. A reduced voltage across a motor winding results in a proportional reduction in the current flowing through the winding and consequently in a reduction of the torque developed, by the square of the reduction in the voltage applied. ½ voltage for example thus means ¼ torque.

A reduction of the voltage across the motor windings can in principle be achieved in one of two ways:

- Reduction of the voltage on the motor while leaving the internal connections of the individual windings unchanged (normally connected in delta). Example: electronic soft starter devices.
- Rearranging the connections of the motor windings so that the voltage on the windings is reduced. Example: Star-delta circuit.

The ratio of the available motor torque to the motor current flowing is different in above cases. This is illustrated with the example of the conventional star-delta circuit compared with the electronic soft starter device (**Fig. 1.7-7**):

				
Starting method	Direct (Δ, delta)	Y (star, wye)	Soft starting	
Current in the pole conductor	100 %	33 %	33 %	57 %
Torque	100 %	33 %	11 %	33 %
Coil voltage	100 %	57 %	33 %	57 %

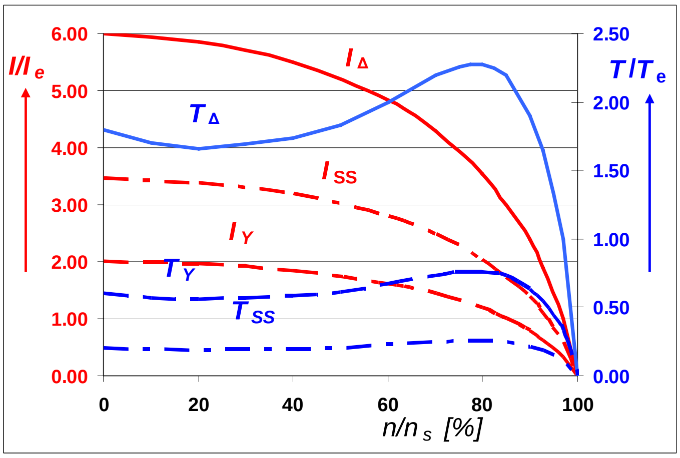


Fig. 1.7-7
Current consumption and torques with direct starting (delta-connected), star-connected starting and starting with the aid of a soft starting device by reducing the voltage across the motor terminals.

I_{Δ}	Current consumption with delta-connected direct starting
T_{Δ}	Torque with delta-connected direct starting
I_{Y}	Current consumption for star-connected starting
T_{Y}	Torque for star-connected starting
I_{SS}	Current consumption when starting by means of soft starting device at torque T_{Y}
T_{SS}	Torque when starting by means soft starting device and same current consumption as for star-connected starting

A startup in star circuit develops a higher torque with the same loading on the power supply, as the voltage across the motor coils is reduced by the circuit change. The windings current is at the same time the pole current, while in the case of a delta-connected motor two windings currents add vectorial (factor $\sqrt{3}$) to the current of the supplying pole.

In relation to the loading of switchgear and its correct selection for starting and operation of squirrel-cage induction motors with voltage reduction, see Sections **3.3, 3.4** and **3.9**, in which the possible solutions are described in detail.

When using soft starting devices, it should be remembered that the line-side switchgear operates the input of the soft starting device, i.e. usually without load. The motor current is subject to harmonics during start-up, which can lead to undesired tripping, especially where electronic protective relays are used.

1.7.1.4 Performance of squirrel-cage induction motors with changing frequency

The basic form of the current and torque characteristic is independent of the frequency. In the sub-synchronous speed range (n = 0 … n_s), the voltage must be reduced in proportion to the frequency to keep the magnetic flux constant and to avoid saturation of the ferromagnetic circuits. This means that the magnitude of the breakdown torque remains roughly constant. Motors that are operated for long periods at lower speeds must be externally ventilated due to the decreasing efficiency of their internal ventilation.

If the frequency rises above the supply frequency then a constant voltage is usually available from the frequency converter. This results in a weakening of the magnetic field with increasing frequency and consequently in a reduction of the breakdown torque in proportion to the square of the frequency. Up to the maximum speed, such drives can typically be operated with constant power output.

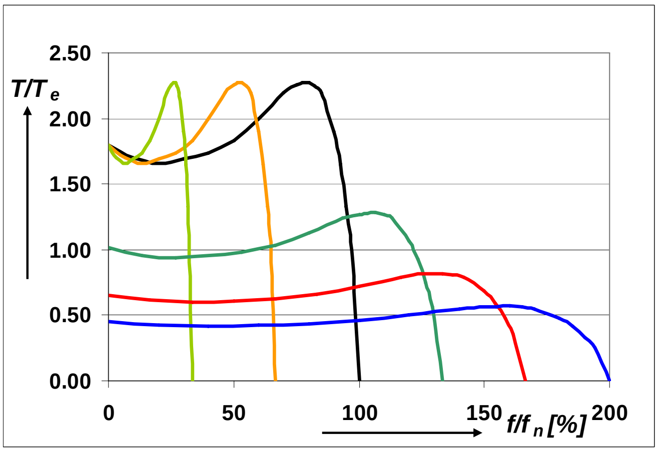


Fig. 1.7-8
Typical torque characteristic with variation of the frequency.
Voltage proportional to frequency in the range 0 … f_n
Voltage constant in the range > f_n

When selecting the line-side switching and protective equipment it should be remembered that frequency converters have large controlled or uncontrolled rectifier circuits on the input-side with large storage capacitances. This results in high charging current surges and in a high harmonic content in the current.

2 Switching tasks and selecting the appropriate switchgear

The selection and use of electrical equipment for switchgear assemblies and machine control units are regulated under the respective national legislation. Within the European Union (EU) the regulations are based on the CENELEC standards (EN standards) which are largely identical with the IEC standards. The IEC standards also form the basis of the applicable regulations in a large number of other countries. In North America, the standards of UL or CSA as well as the directives of NEMA, NEC etc. have to be applied. All these standards and regulations have as their common goal to guarantee the safety of electrical installations.

2.1 Electrical equipment complying with standards and matching the application requirements

The standards IEC 60439-1 (Low-voltage switchgear and controlgear assemblies) and IEC 60204-1 (Electrical equipment of machines) require among other things that the electrical equipment must correspond to the valid applicable standards. This means that low-voltage switchgear must be built and tested in compliance with the requirements of IEC 60947. Furthermore, the external design of the electrical equipment, its rated voltages, rated currents, life span, the making and breaking capacity, the short-circuit withstand capacity etc. must be suitable for the respective application. If necessary current-limiting protective devices must be used for protecting the electrical equipment. The coordination of electrical equipment, for example of motor starters to short-circuit protection equipment must comply with the applicable norms. When selecting electrical equipment the rated impulse withstand voltages and the generated switching overvoltages have to be considered.

According to these standards, all devices that are available on the market must comply with the applicable standards. For the EU and the EEA, this compliance is confirmed by a declaration of conformity by the manufacturer and the CE-sign. The same requirements apply to Switzerland, with the exception that the CE-sign is not compulsory (but is permitted). Other countries have their own licensing procedures and signs of conformity. So requires China the CCC-mark and Australia and New Zealand have introduced the C-tick-mark for EMC compliance of electronic products.

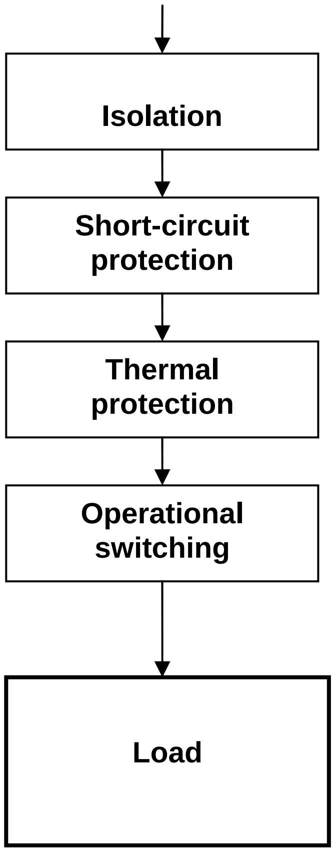
Fig. 2.1-1
CE-sign for the EU market (left), CCC-sign for China (center) and C-tick-mark for Australia and New Zealand

For special applications such as for example shipping, railroads or applications in hazardous environments where a risk of explosion exists, specific regulations apply in many cases that usually contain additional requirements beyond the basic IEC standards.

The standards to which the devices have been built and tested are listed in the catalogs. For low-voltage switchgear (contactors, motor starters, circuit breakers, load switches etc.) for the markets outside North America, these standards are basically the various parts of the IEC 60947.

2.2 Basic switching tasks and criteria for device selection

Load circuits include functional components in accordance with **Fig. 2.2-1**, whereby several functions can be combined in a single device.



Example
Disconnector (Isolator)
Switch disconnector
Circuit breaker with isolating function

Fuse
Circuit breaker

Fuse (line protection)
Circuit breaker with thermal release
Motor protection relay (thermal, electronic)

Contactor
Load switch
Motor protection circuit breaker

Motor
Heater
Lighting
Capacitor

Fig. 2.2-1
Functional elements of a load circuit

The selection of suitable devices to fulfill the required functions is based on the characteristics of the load (e.g. rated power and utilization category), the operational requirements (e.g. switching frequency, required availability after a short-circuit) and the nature of the power supply (e.g. rated voltage, prospective short-circuit current).

2.2.1 Device types

Various types of device are available for carrying out the switching and protection tasks listed under **2.2** that are specially designed to fulfill the respective requirements. The various parts of IEC 60947 (Low-voltage switchgear and controlgear) specify the design, performance and test features of the devices. The most important features of the main device types are presented below.

2.2.1.1 Disconnectors (isolating switches)

The disconnector is a mechanical switchgear that fulfills in the open position the requirements specified for the isolation function (IEC 60947-1). The purpose of the isolating function is to cut off the supply from all or a discrete section of the installation by separating the installation or section from every source of electrical energy for reasons of safety. The key factor here is the opening distance. Isolation must be guaranteed from pole to pole and from input to output, whether this is by means of a visible isolation gap or by suitable design features within the device (mechanical interlocking mechanism).

A device fulfills the isolating function stipulated under IEC 60947-1 when in the “Open” position the isolation at a defined withstand voltage is assured between the open contacts of the main circuit of the switchgear. It must also be equipped with an indicator device in relation to the position of the movable contacts. This position indicator must be linked in a secure, reliable way to the actuator, whereby the position indicator can also serve as actuator, provided that it can only display the position “Open” in the “OFF” position, when all moving contacts are in the “Open” position. This is to be verified by testing.

According to IEC 60947-3, an isolator must only be able to make and break a circuit, if either a current of negligible size is switched on or off, or if during switching no noticeable voltage difference between the terminals of each pole occurs. Under normal conditions it can conduct operational currents as well as under abnormal conditions larger currents (e.g. short-circuit currents) for a certain period.

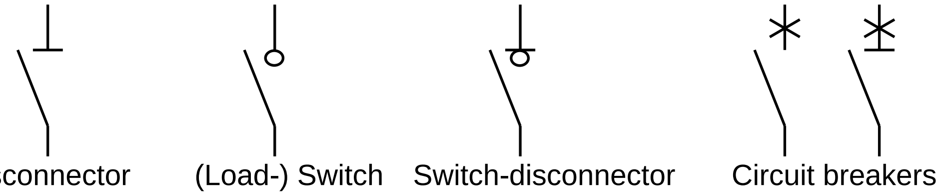


Fig. 2.2-2
Switch symbols
The horizontal line in the switch symbol of the contacts indicates that they fulfill the isolating function

The isolator function can be realized with a variety of devices such as for example in disconnectors, fuse-disconnectors, switch-disconnectors, fuse-switch disconnectors and circuit breakers with isolating function.

2.2.1.2 Load switches

Load switches (or only “switches”) are mechanical switching devices capable of making, carrying and breaking currents under normal circuit conditions which may include specified operating overload conditions and also carrying for a specified time currents under specified abnormal circuit conditions such as those of short-circuit.

A load switch may have a short-circuit making capacity, however it does not have a short-circuit breaking capacity (IEC 60947-1 and -3). Short-circuit currents can be conducted (high short-circuit withstand capacity), but not be switched-off.

For load switches the range of designs is similarly wide as for isolator switches, for example “normal” (load) switches, fuse-switches, circuit breakers. Fuse-switches are not legally permitted in all countries.

2.2.1.3 Switch disconnectors

Switch disconnectors combine the properties of (load) switches and disconnectors.

In this case, too, there are a variety of designs such as “normal” switch disconnectors, fuse-switch-disconnectors and circuit breakers. Fuse-switch-disconnectors are not legally permitted in all countries.

2.2.1.4 Circuit breakers

See also Section **4.2.2**. Circuit breakers are mechanical switching devices, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal circuit conditions such as those of short-circuit (IEC 60947-2). They thus also fulfill the requirements of (load) switches. Circuit breakers are often designed so that they can fulfill the requirements for disconnectors.

2.2.1.5 Supply disconnecting devices

IEC 60204-1 (Machine safety – Electrical equipment of machines) requires a supply disconnecting (isolating) device for each incoming source of supply and for each on-board power supply that completely isolates the machine or the device from the external or internal power supply for the machine, so that cleaning, maintenance and repair work can be carried out or the machine can be shut down for longer periods of time.

- A supply disconnecting device must fulfill the requirements of a switch-disconnector as defined in IEC 60947-3 (load switch with isolating function) and at the least fulfill the requirements of utilization categories AC-23B or DC-23B. Disconnectors are permitted if load shedding is assured by an auxiliary contact before opening of the main contacts of the disconnector. Also circuit breakers with isolating function or other switchgear with isolating function and motor switching capacity can be used as supply disconnecting devices, provided that they fulfill the corresponding IEC standards.

- A supply disconnecting device must be manually actuated and have unambiguous “ON” and “OFF” positions that are clearly marked with “O” and “I”.
- A supply disconnecting device must either have a visible contact gap or a position indicator which cannot indicate OFF (isolated) until all contacts are actually open and the requirements for the isolating function as specified under IEC 60947-3 have been satisfied.
- If the supply disconnecting device does not simultaneously serve as EMERGENCY STOP device, it may not have a red handle (preferred colors black or gray).
- It must be possible to lock the handle in the “OFF” position (for example with a padlock).
- The supply-side terminals of supply disconnecting devices must be equipped with a finger protection anti-tamper shield and a warning sign.

If required, supply disconnecting devices may be equipped with a door interlock device.

The power supply of the below circuits does not necessarily have to be controlled via the supply disconnect switch:

- Lighting circuits that are required for maintenance work
- Sockets that are exclusively used for service equipment such as drills.

The requirements for supply disconnect switches can be fulfilled by switch-disconnectors, fuse-switch-disconnectors and circuit breakers.

2.2.1.6 Supply disconnecting EMERGENCY STOP devices

If there is a real and present danger for man or machine, the dangerous parts of the machine or the entire machine must be disconnected from the power supply by actuation of an EMERGENCY STOP device as quickly as possible and brought to a standstill. According to IEC 60204-1 supply disconnecting devices are acceptable as local EMERGENCY STOP devices as long as they are easily accessible for operating personnel. The below conditions must also be fulfilled:

- For use as an EMERGENCY STOP device the handle must be red and on a yellow background.
- The device must be simultaneously able to interrupt the locked-rotor current of the largest connected motor plus the sum of the rated currents of the remaining loads.
- It must be able to conduct the total rated operational current of all connected devices.
- The EMERGENCY STOP switch may not break those circuits that could lead to endangerment of the personnel or the machine.

2.2.1.7 Summary supply disconnect and EMERGENCY STOP devices

Requirements on supply disconnect devices (under IEC 60204-1)	**Supply disconnect devices**	**Supply disconnect/ EMERGENCY STOP devices**
Operator handle:		
- Black or gray handle	yes	no
- Red handle with yellow background	no	yes
- Lockable	yes	yes
Manual actuation from outside	yes	yes
Easily accessible	yes	yes
Only one “ON” and “OFF” position	yes	yes
Position indicator only “O” and “I”	yes	yes
Lockable in “O” position from outside	yes	yes
Touch-protected input terminals with warning symbol	yes	yes

Tab. 2.2-1
Summary of requirements on switches for use as supply disconnect devices and supply disconnect/EMERGENCY STOP devices

2.2.1.8 Fuses

Fuses have a short-circuit breaking capacity and in the form of full-range fuses are also suitable for overload protection of conductors and certain loads. For details see Section **4.2.1**.

2.2.1.9 Devices for thermal protection

See Sections **4.1.2**, **4.2** and **4.2.4**.
Devices for thermal protection are divided into two groups:

- Devices that evaluate the thermal risk to the protected object and provide a protective disconnection in one unit (for example full-range fuses, MCB’s, circuit breakers, motor-protection circuit breakers, electronic motor control devices with integrated motor protection) and
- Devices that exclusively evaluate the thermal risk to the protected object but for protective shutdown control a power switching device (usually a contactor). These include for example overload relays and thermistor (PTC) protection devices.

2.2.1.10 Contactors

Contactors are designed for operational switching and - in accordance with the required high mechanical and electrical life span - use relatively low contact forces. Accordingly they have no short-circuit switching capacity and must be protected against the effects of short-circuit currents by series-connected short-circuit protective devices. See Section **2.3.4.5**.

2.3 Parameters for the correct selection and sizing

For the specific application of low-voltage devices additional parameters should be taken into account such as for example the application ambient temperature, the expected device life span, any influences from moisture, mechanical impacts and vibrations etc., to name only a few of the most important. **Tab. 2.3-1** provides a summary of the most important parameters when selecting devices. Some of the specific features are looked at in more detail below.

Parameter	**Details chapter**	**Disconnectors**	**Fuses**	**Circuit breakers**	**Load switches**	**Contactor Starters**
Rated isolation voltage U_i	2.3.1	P	P	P	P	P
Rated operational voltage U_e ($<U_i$)	2.3.2	P	P	P	P	P
Rated impulse withstand voltage U_{imp}	2.3.3	P		P	P	P
Rated operational current I_e	2.3.2	P	P	P	P	P
Utilization category	2.3.2	P		P	P	P
Short-circuit withstand capacity / short-circuit protection	2.3.4	P			P	P
Rated short-circuit making capacity I_{cm}	2.3.4.6.1			P	P	
Rated short-circuit breaking capacity I_{cu}, I_{cs}	2.3.4.6.2		P	P		
Cut-off current	2.3.4.2 2.3.4.4		C	C		
Let-through energy (Joule integral)	2.3.4.1 2.3.4.4		C	C		
Rated short time current I_{cw}	2.3.4.3	C		C	C	
Short-circuit coordination (Type 1, Type 2) with fuses or circuit breakers	2.3.4.5.2					P
Thermal load	2.3.5	P		P	P	P
Ambient temperature	2.3.5.1	C	C	C	C	C
Operational overcurrents (for example heavy-duty starting)	2.3.5.2	C	C	C	C	C
Life span	2.3.6				C	C
Frequency of operation	2.3.7				C	C
Rated frequency / harmonics	2.3.8 2.4.3	C	C	C	C	C
Safety clearances	2.3.9			P	P	P
Mounting position	2.3.10			C		C
Pollution degree	2.3.3	A	A	A	A	A
Overvoltage category	2.3.3	A	A	A	A	A
Protective separation	2.3.11	A	A	A	A	A
Site altitude	2.3.12	A	A	A	A	A
Shock and vibration	2.3.13	A	A	A	A	A
Humidity / climatic loading		A	A	A	A	A
Chemical ambient influences		A	A	A	A	A
Radioactive radiation		A	A	A	A	A
UV radiation		A	A	A	A	A
External form / IP degree of protection		A	A	A	A	A

Tab. 2.3-1
Selection criteria for low-voltage switchgear for main circuits
P … Primary selection factors
C … Complementary selection factors
A … Additional criteria

2.3.1 Rated isolation voltage U_i

U_i is the voltage on which the selection of creepage distances of electrical equipment and the dielectric tests are based. U_i must always be bigger than (or at least the same as) the voltage that is applied to the electrical equipment and is thus always larger than or the same size as the rated operational voltage U_e. With the selection of U_e is thus U_i (in the responsibility of the device manufacturer) correctly selected, whereby the pollution degree and the overvoltage category should be taken into account.

2.3.2 Rated operational voltage U_e, rated operational current I_e and utilization category

The rated operational voltage U_e is always to be considered in association with the corresponding rated operational current I_e and the utilization category. These three variables determine the suitability of an item of electrical equipment for a certain application. For utilization categories see Section **1.1**.

Corresponding to the universal applicability, an item of electrical equipment can be assigned a variety of different datasets (for example I_{eAC-3} for various operational voltages or I_{eAC-3} and I_{eAC-4} for a certain operational voltage). Common values for rated operational voltages for switchgear can be seen in **Tab. 2.3-2**. With 3-phase supply systems, the delta (phase to phase) voltage of the power supply applies.

Supply voltages		Supply voltages for three-phase 4-wire or 3-wire systems	
d.c. V	a.c. V	50 Hz V	60 Hz V
6	6		
12	12		
24	**24**		
36			
48	48		
60			
72			
96			
110	**110**		120/208
220	**230**	**230/400**	240
			277/480
440		**400/690**	347/600
			600
		1000	

Tab. 2.3-2
Preferred rated voltages for supply systems in accordance with IEC 60038 ed. 6.2 and industrial practice (L-N/L-L). Copyright © IEC, Geneva, Switzerland. www.iec.ch

2.3.3 Rated impulse withstand voltage U_{imp}

The rated impulse withstand voltage U_{imp} is a measure for the dielectric strength. From the point of view of the user it is important, as the required dielectric strength among other things depends on the pollution degree of the installation site and the overvoltage category, i.e. the proximity to the feeding supply network. With respect to the pollution degree see **Tab. 2.3-3**. **Tab. 2.3-4** shows as an excerpt from Table H.1 of IEC 60947-1 Annex H the influence of the overvoltage category on the applicable impulse withstand voltage U_{imp}. The rated impulse withstand voltage is for example important in circuit breakers that are often deployed on the distribution level or also on the supply level.

6.1.3.2 Pollution degree

The pollution degree (see 2.5.58) refers to the environmental conditions for which the equipment is intended.

NOTE 1 The micro-environment of the creepage distance or clearance and not the environment of the equipment determines the effect on the insulation. The micro-environment might be better or worse than the environment of the equipment. It includes all factors influencing the insulation, such as climatic and electromagnetic conditions, generation of pollution, etc.

For equipment intended for use within an enclosure or provided with an integral enclosure, the pollution degree of the environment in the enclosure is applicable.

For the purpose of evaluating clearances and creepage distances, the following four degrees of pollution of the micro-environment are established (clearances and creepage distances according to the different pollution degrees are given in Tables 13 and 15):

Pollution degree 1:

No pollution or only dry, non-conductive pollution occurs.

Pollution degree 2:

Normally, only non-conductive pollution occurs. Occasionally, however, a temporary conductivity caused by condensation may be expected.

Pollution degree 3:

Conductive pollution occurs, or dry, non-conductive pollution occurs which becomes conductive due to condensation.

Pollution degree 4:

The pollution generates persistent conductivity caused, for instance, by conductive dust or by rain or snow.

Standard pollution degree of industrial applications:

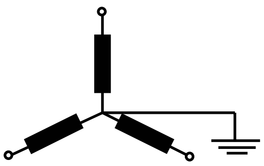
Unless otherwise stated by the relevant product standard, equipment for industrial applications is generally for use in **pollution degree 3** environment. However, other pollution degrees may be considered to apply depending upon particular applications or the micro-environment.

NOTE 2 The pollution degree of the micro-environment for the equipment may be influenced by installation in an enclosure.

Standard pollution degree of household and similar applications:

Unless otherwise stated by the relevant product standard, equipment for household and similar applications is generally for use in **pollution degree 2** environment.

Tab. 2.3-3
Pollution degree according to IEC 60947-1 ed. 5.0.

Maximum value of rated operational voltage to earth	Nominal voltage of the supply system (≤ rated insulation voltage of the equipment) a.c. r.m.s. V	Preferred values of rated impulse withstand voltage (1,2/50 µs) at 2 000 m kV			
a.c. r.m.s. or d.c. V		Overvoltage category			
		IV	III	II	I
		Origin of Installation (service entrance) level	Distribution circuit level	Load (appliance, equipment) level	Specially protected level
300	220/380, 230/400, 240/415, 2607440 277/480	6	4	2.5	1.5
600	347/600, 380/660, 400/690, 415/720 480/830	8	6	4	2.5
1000	-	12	8	6	4

Tab. 2.3-4
Correspondence between the nominal voltage of the supply system and rated impulse withstand voltage of the device with protection by surge-arrestors according to IEC 60099-1
Excerpt from Table H.1 of IEC 60947-1 ed. 5.0 Annex H

2.3.4 Short-circuit withstand capacity and short-circuit protection

See also Section **4.1.3**.

Adequate protection against the consequences of a short-circuit is one of the most fundamental safety measures for electrical equipment. This affects both the protection of persons as well as of property. For operational reasons it is often desirable that devices survive short-circuits largely unscathed so that they may become operational again as quickly as possible afterward. The specification of coordination types for starters is also related to this requirement.

The short-circuit withstand capacity of electrical equipment is usually defined by stating the largest permitted short-circuit protective device (for example permissible fuse or permissible circuit breaker). Current limiting fuses and modern current limiting circuit breakers make a major contribution to the economical rating of devices, as they strongly reduce the thermal and dynamic loading of devices and equipment connected downstream.

Loading in the event of a short-circuit is defined by the Joule integral (I^2t value), the cut-off current (I_D) and the short-time current (I_{cw}).

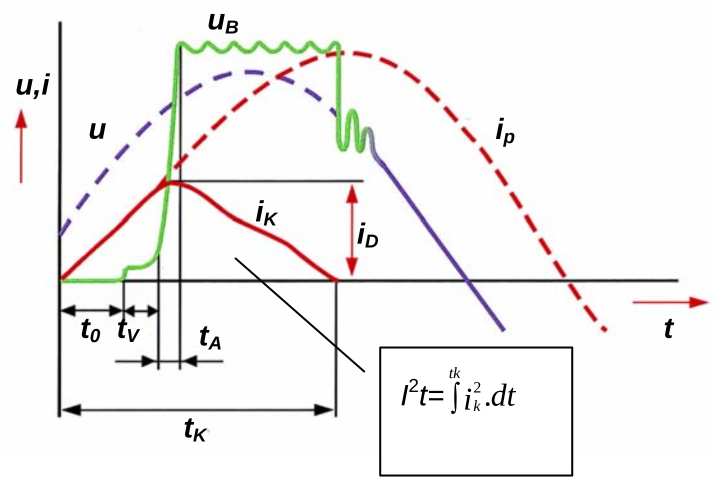


Fig. 2.3-1
Basic characteristic of current and voltage when clearing a short-circuit with a current limiting circuit breaker

u	*System voltage*
u_B	*Electric arc voltage*
i_p	*Prospective peak short-circuit current*
i_K	*Limited short-circuit current*
i_D	*Cut-off current*
t_0	*Inherent system delay*
t_V	*Electric arc hesitation time*
t_A	*Rise time*
t_K	*Total break time*

2.3.4.1 Joule integral I^2t

The I^2t-value is a measure of the thermal loading of the electrical equipment in the shorted circuit. Fuses and current limiting circuit breakers limit the short-circuit current to values significantly below those of the uninfluenced current and thus reduce the thermal loading of the devices in the shorted circuit, for example of the contact system of a contactor connected downstream. The rule of thumb is that the Joule integral of the short-circuit protective device must be smaller than the permissible I^2t-value of the conductor and of the electrical equipment to be protected.

2.3.4.2 Cut-off current I_D

The cut-off current is the largest instantaneous value of the current that a current limiting short-circuit protective device allows through. As the action of the force of the electrical current is proportional to the square of the current, the cut-off current is critical in ensuring the required mechanical strength of connected electrical equipment. This is particularly relevant for the design of bus systems (number and strength of the supports). IEC 60439 takes this circumstance into account by dispensing from the requirement of verification of the short-circuit withstand capacity for cut-off currents ≤ 17 kA.

2.3.4.3 Rated short-time withstand current I_{CW}

Like the Joule integral, the short-time withstand current I_{CW} is a measure of the thermal load capacity. It is important for circuit breakers of category B (suitable for selectivity) and is usually stated as the 1s-current (preferred values under IEC 60947-2 are 0.05, 0.1, 0.25, 0.5 and 1 s). A conversion of I_{cw} currents for other durations is permitted according to the equation

$$I_{cw1}^2 \cdot t_1 = I_{cw2}^2 \cdot t_2 = \text{const.}$$

The I_{cw}-value is of importance when for selectivity reasons the breaking action of circuit breakers is delayed. The circuit breakers in the shorted circuit must be able to carry the short-circuit current until the delay time has expired and then shut down the shorted circuit. For circuit breakers with $I_n \leq 2500$ A, IEC 60947-2 requires $I_{CW} \geq 12 \cdot I_n$, at least 5 kA. For $I_n > 2500$ A $I_{CW} \geq 30$ kA is required.

2.3.4.4 Current limiting protective equipment

If the short-circuit withstand capacity of electrical equipment is lower than the prospective short-circuit current at the installation site, its loading must be reduced in the case of a short-circuit by upstream current limiting protective equipment to the permissible magnitude. For this purpose fuses or current limiting circuit breakers may be chosen.

The I^2t- and i_D-values of this protective equipment are – usually in diagrams – stated as a function of the prospective short-circuit current I_{cp} (see example **Fig. 2.3-2**). It should be noted that these quantities vary with the operating voltage. For fuses, limit-curves can be found in the diagrams for the cut-off current for the largest and without direct current component (see example **Fig. 2.3-3**). As the time of occurrence of a short-circuit is coincidental, the cut-off current for the largest direct current component is critical for engineering (i.e. most unfavourable time point of occurrence of the short-circuit).

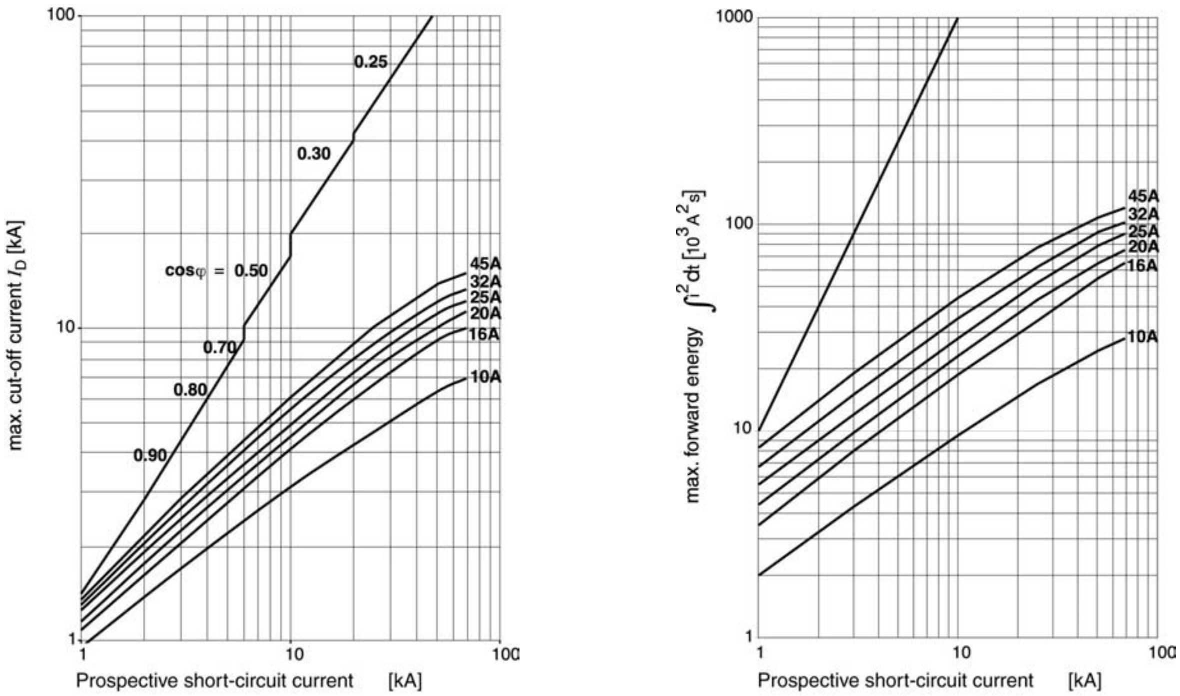


Fig. 2.3-2
i_D-values and I^2t-values as a function of the prospective short-circuit current I_{cp}

When the cut-off current is limited to ≤ 17 kA, in accordance with IEC 60439-1 no verification of the short-circuit withstand capacity for the downstream circuits is required. This relates in particular to the mechanical strength of the conductors. For the protection of electrical equipment (for example of motor starters) smaller cut-off currents may also be required.

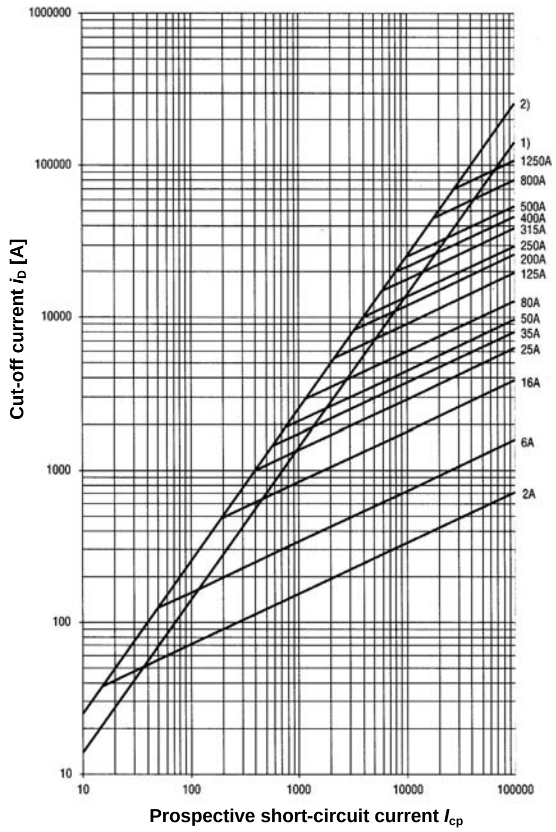


Fig. 2.3-3
Example of an i_D-diagram for fuses as a function of the prospective short-circuit current I_{cp}
1) Peak short-circuit current without direct current component
2) Peak short-circuit current with maximum direct current component

2.3.4.5 Coordination of electrical equipment

The coordination of electrical equipment refers to the assignment of short-circuit protective devices to contactors or starters with respect to the effects of a short-circuit on these devices. Distinction is made between two types of coordination:

- The coordination of the trip characteristic of the overload relay (if present) with the protective characteristic of the short-circuit protective device in respect of the switching capacity of the contactor
- The coordination between the short-circuit protective device, the contactor and the overload relay with respect to the destructive effect of a short-circuit and their operability afterward.

2.3.4.5.1 Coordination in respect of the switching capacity of the contactor (overcurrent selectivity)

The coordination between the release characteristic of the overload relay and the short-circuit protective device takes account of the switching capacity of the contactor. Contactors are designed for the operational switching of loads and are not able to switch-off currents of short-circuit level. The coordination of the devices must ensure that for currents above the switching capacity of the contactor the short-circuit protective device shuts down before the overload relay is responding and dropping-out the contactor (**Fig. 2.3-4** and **Fig. 2.3-5**).

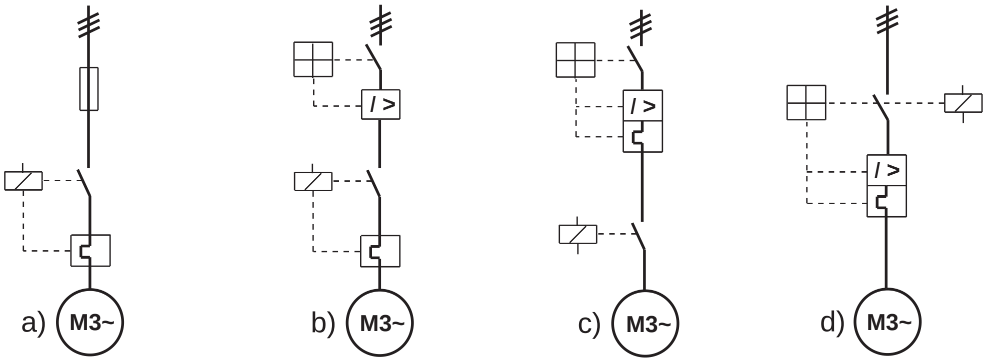


Fig. 2.3-4
Types of load feeders (with electromechanical switchgear)
a) Fuse, contactor, motor protection relay
b) Circuit breaker with magnetic release, contactor, motor protection relay
c) Circuit breaker with motor protection characteristic, contactor
d) Operational switching and circuit breaker function combined in one contact system

For starters that are protected by circuit breakers with motor protection characteristic, no coordination with respect to the overcurrent selectivity is required, as circuit breakers switch-off in the event of overloads and short-circuits.

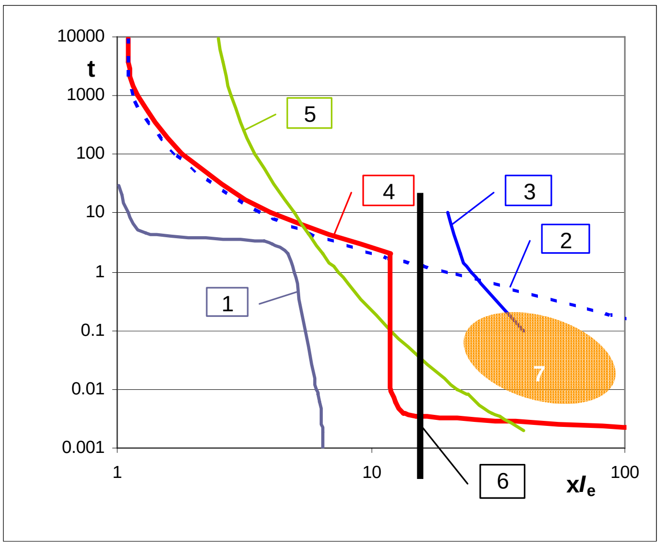


Fig. 2.3-5
Short-circuit coordination of switching and protective devices. Circuit breakers with motor protection characteristic are used as an alternative to fuse/overload relay.

1	*Motor starting current*
2	*Trip characteristic overload relay*
3	*Destruction limit curve overload relay*
4	*Trip characteristic circuit breaker with motor protection characteristic*
5	*Time/current-characteristic fuse (alternative to circuit breaker)*
6	*Rated breaking capacity of the contactor*
7	*Welding area of the contactor*

2.3.4.5.2 Coordination with respect to the operability after a short-circuit

The coordination of contactor and overload relay, if any, with a short-circuit protective device with respect to the operability of starters after a short-circuit is determined by the destructive or damaging effect of the short-circuit current on the starter components. Basic requirement – regardless of coordination type – is that neither persons nor equipment may be endangered.

- **Coordination type 1** permits damage to the starter so that further operation may only be possible after repair or replacement.
- With **coordination type 2** the contactor or starter must be suitable for further use after the short-circuit. Slight welding of contacts is acceptable. An early replacement of the starter components is usually required (depending on the severity of the short-circuit) due to the erosion of contact material by the short-circuit current, however this can be carried out at an operationally convenient time.
- **Coordination type "CPS"** requires in accordance with IEC 60947-6-2 that a load feeder continues to be usable after a short-circuit, in order to maximize operational continuity. The guaranteed residual electrical life span based on a new device is 6000 cycles. In this case too, the replacement of the starter components as in coordination type 2 is required and may be carried out at a time that is convenient from an operational viewpoint. Load feeders under coordination type "CPS" can be realized in any design (see also **Fig. 2.3-4**).

	Type "1"	Type "2"	Type "CPS"
Finding and rectifying cause of short-circuit	X	X	X
Checking starter	X	X	
Replacing devices	X	1)	1)
Separating welded contacts, if any		X	
Resume operation	X	X	X
Planned maintenance (device replacement)		X	X

Tab. 2.3-5
The selection of the coordination type with respect to duration of the interruption to operation
1) Replacement of fuses, if used

2.3.4.6 Short-circuit switching capacity

The switching capacity is the r.m.s value of a current at a given power factor cos φ as well as a given rated voltage at which a switchgear or a fuse can still shut-off under specified conditions in an operationally safe way. Both the short-circuit making capacity as well as the short-circuit breaking capacity of circuit breakers must be larger than or equal to the prospective short-circuit current at the place of installation. If this is not the case, then a suitable backup protection (for example a fuse) should be provided to ensure the required switching capacity of the device-combination. Data regarding devices for backup protection are given in the technical documentation.

2.3.4.6.1 Rated short-circuit making capacity I_{cm}

The rated short-circuit making capacity I_{cm} is a quantity that according to regulations must be in a certain ratio to the rated ultimate short-circuit breaking capacity I_{cu} and that has to be guaranteed by the device manufacturer. This is not a variable that must be considered by the user, however it ensures that a circuit breaker is in the position to connect onto a short-circuit – and to disconnect it subsequently.

2.3.4.6.2 Rated short-circuit breaking capacity I_{cu} and I_{cs}

IEC 60947-2 makes distinction between the rated ultimate short-circuit breaking capacity I_{CU} and the rated service short-circuit breaking capacity I_{CS}:

- Rated ultimate short-circuit breaking capacity I_{CU}:

  I_{CU} is the maximum breaking capacity of a circuit breaker at an associated rated operational voltage and under specified conditions. I_{CU} is expressed in kA and must be at least as large as the prospective short-circuit current at the site of installation.
  Circuit breakers that have switched-off at the level of the ultimate short-circuit breaking capacity, are reduced serviceable afterwards and should at least be checked regarding functionality. There may be changes in the overload trip characteristic and increased temperature rise due to the erosion of contact material.

- Rated service short-circuit interrupting capacity I_{CS}:

  I_{CS} values are usually lower than the values for I_{CU}. Circuit breakers that have been switching-off at the level of the service short-circuit breaking capacity continue to be serviceable afterward. In plants in which interruptions to operations must be kept as short as possible, product selection should be carried-out based on I_{CS}.
- Breaking capacity of fuses
  The same applies to fuses as to circuit breakers with respect to the I_{CU}: at the given rated operational voltage, the rated breaking capacity must be at least as large as the prospective short-circuit current at the site of installation.

2.3.5 Thermal protection

Compliance with the permissible operational temperatures of electrical equipment is both a vital safety factor as well as critical regarding its effective life span. The rate of ageing of plastics increases exponentially with their operational temperature.

For all electrical equipment, limiting values for the load currents are defined, compliance with which should be ensured by suitable protective devices and measures (fuses, overload relays, temperature sensors).

2.3.5.1 Ambient temperature

Electrical equipment is designed for operation in defined temperature ranges. The upper temperature limit is of special importance, because practically all electrical equipment dissipates power and hence produces heat. The selection of the devices must consider the device's ambient temperature and the permitted load at this temperature.

The normal ambient temperature range under IEC 60947, IEC 60439 and IEC 60204 is –5 °C to +40 °C with a 24-hour average that does not exceed +35 °C. It should be noted that the rated values of the current load capacity unless otherwise stated are related to an ambient temperature of +40 °C. With other (higher) temperatures the loads should be reduced in accordance with manufacturer specifications or larger devices should be chosen. For industrial switchgear, loading specifications are often provided for an ambient temperature of +55 or +60 °C.

The lower limit of the operational temperature may be critical with electronic devices and it should be assured by provision of heating that temperature does not fall below. In conjunction with moisture (freezing), low temperatures can also adversely affect the operability of electromechanical devices.

Rated operational values designated as “open” apply for devices used in free air, while values designated “enclosed” apply for devices installed in an enclosure of small size specified by the manufacturer. The reference ambient temperature for “open” is the temperature of the ambient air of the device, even if this is installed in a box or cabinet. The reference ambient temperature for “enclosed” is the air-temperature of the housing environment. The ambient temperature of the device in the housing is higher because of the effect of its own heat dissipation. In practice this means for example that for a contactor “open” at 60 °C I_{th} = 20 A will be stated and “enclosed” at 40 °C the same value, because due to heating in the housing the contactor is subjected to the same immediate ambient temperature of 60 °C. At 40 °C “open” the same contactor can for example conduct 25 A.

In switchgear, in which the temperature in the cabinet (see Software TRCS) is calculated or measured, the data for “open”, that is in the immediate device environment (microclimate) should be taken into account when selecting the devices. It should be ensured by temperature monitoring and cooling measures that the actual temperature does not exceed the reference value on which the component selection is based.

2.3.5.2 Operational overcurrents, heavy-duty starting

Operational overcurrents occur especially when motors are started. Switchgear such as contactors or load switches should be rated so that it can cope with the regularly occurring overcurrents without difficulty, assuming it has been selected in accordance with the corresponding utilization category. Motor starts that cause normal motor protection relays of trip class 10 (tripping between 4 and 10 s at 7.2 · I_e) to trip are considered as heavy-duty starts. In these cases overload protective relays with slower trip characteristics should be selected. See also **1.7.1.2.1**.

In addition the load capacity of the switchgear should be checked.

The load capacity of contactors and circuit breakers without thermal release basically depends on their size (cross-section/mass of the conducting parts). It therefore varies from device to device. Up to a starting time of around 10 s for direct starting, the load of the devices during starting needs not to be checked. Furthermore the admissible load capacity can be obtained from the technical documentation (catalog, RALVET; see example **Fig. 2.3-6**). Rest times should be allowed between successive heavy-duty starts that provide sufficient time for the switchgear (see RALVET) and the motor to cool down before the next loading.

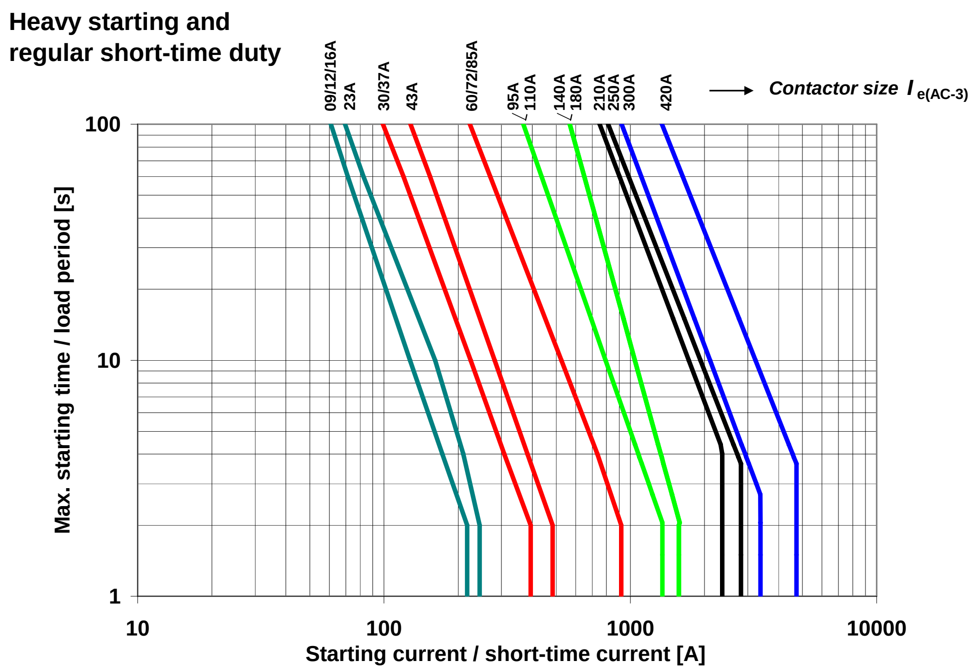


Fig. 2.3-6
Example of a loading diagram for contactors for heavy-duty starting of squirrel-cage induction motors

2.3.6 Life span

The life span of switchgear basically depends on the size of the load and the number of switching cycles. Instead of a time span, with electromechanical switchgear reference is usually made to the number of operations, as the ageing mainly depends on the stress during switching and less on the on- and off-phases between. The maximum number of operations is usually determined by the wear of heavily loaded components – in contactors, load switches and circuit breakers especially of the contact system.

For switchgear, the mechanical and electrical life spans are separately defined. The mechanical life span states the number of possible operations without electrical loading, while the electrical life span states the number of operations for a certain size of electrical loading and a certain utilization category.

In electronic devices, the life span is usually less dependent on the number of operations but rather on the working temperature. Thus for example electrolytic capacitors (for example used in power adapters) age more quickly at higher temperatures. This is why it is recommended to install electronic devices in the cooler parts of switch cabinets.

Ageing is also a problem with fuses, especially in the context of switching of motors. Full-range fuses (gL, gG) have a soldered joint for tripping in the overcurrent range that may age due for example to repeated short-term melting. When using them with motors with the latters' high starting currents, it should therefore be ensured that the starting current does not raise the temperature of this solder joint beyond a certain limit. Fuse manufacturers provide information on the smallest fuses that can be selected in relation to given motor currents and starting times.

2.3.6.1 Prospective service life

The prospective service life of switchgear is the number of years, months or weeks that it should complete under the foreseen service conditions in 1-, 2- or 3-shift operation without the replacement of spare parts. It depends on the frequency of operation and the total number of individual switching operations. For the latter in addition to the mechanical also the electrical life span of the devices must be selected accordingly (see Section **2.3.6.3**). The required parameters can be determined by means of the below formulae:

$$n_{tot} = f_S * h_D * d_Y * n_Y$$

$$n_Y = \frac{n_{tot}}{f_S * h_D * d_Y}$$

$$f_S = \frac{n_{tot}}{n_Y * h_D * d_Y}$$

n_{tot} Total number of operations (life span)
f_S Switching operations per hour
h_D Operating hours per day
d_Y Operating days per year
n_Y Number of years (life span)

2.3.6.2 Mechanical life span

The mechanical life span of switchgear is the total number of possible switch operations without electrical switch loading. It depends on the design, the masses moved, the forces and accelerations occurring. Large load switches and circuit breakers operate with high contact forces and large masses, and therefore have a comparatively short mechanical life span. On the other hand, contactors operate with relatively small contact forces and thus achieve longer mechanical life spans.

After the mechanical life span has expired, the devices must be replaced. This life span is only rarely achieved during the foreseen service life. In a few cases, where the complete mechanical life span has to be used, it should be ensured that it is not reduced by adverse ambient conditions, installation position and – in the case contactors – by an excessive control voltage.

2.3.6.3 Electrical life span

The electrical life span for switchgear is the number of possible switching operations under operational conditions. After this number has been reached, the parts subject to wear must be – wherever possible – replaced. With small devices, the entire device must be replaced.

Depending on the application, the loading and the resulting erosion of the contacts varies widely. This is influenced by the following conditions, whereby the first mentioned play the dominant role:

- Breaking current
- Making current
- Voltage
- Power factor cos φ with alternating current
- Time constant τ with direct current
- Frequency of operation
- Malfunctions in the plant and on other devices (contact chatter)
- Ambient conditions (climate, temperature, vibrations)

Usually the electrical life span determined under test conditions is presented in diagrams as a function of the rated operational current. These values may generally be used without hesitation in contactor selection. In practical operation, the loads are usually lower, as the running motor usually carries a current that is below the rated operational current. In the case of longer inching operation, the starting current has already dropped somewhat by the time the motor is switched-off. This usually compensates for the effect of any disregarded adverse conditions.

For the most common applications of contactors the electrical life span is presented in the product documentation with various diagrams:

- **AC-1** Non-inductive or slightly inductive loads, for example resistance furnaces (small making current and cos φ higher than with AC-3, however full recurring voltage on switching off)
- **AC-3** Squirrel-cage induction motors: Starting, switching off motors during running (high making current, breaking of the motor rated current)
- **AC-2** Slip-ring motors: Starting, switching off
- **AC-4** Squirrel-cage motors: Starting, plugging, inching (high making and breaking current at full voltage)

- **Mixed service** of slip-ring motors, e.g.
  AC-3 90 %
  AC-4 10 %

With the curves **Fig. 2.3-7** for AC-3 and **Fig. 2.3-8** for AC-4 the expected electrical life span for specific applications can be determined. These curves also can be used to determine the electrical life span for any application (for example jogging motors with very high or especially low starting current and any mixed service).

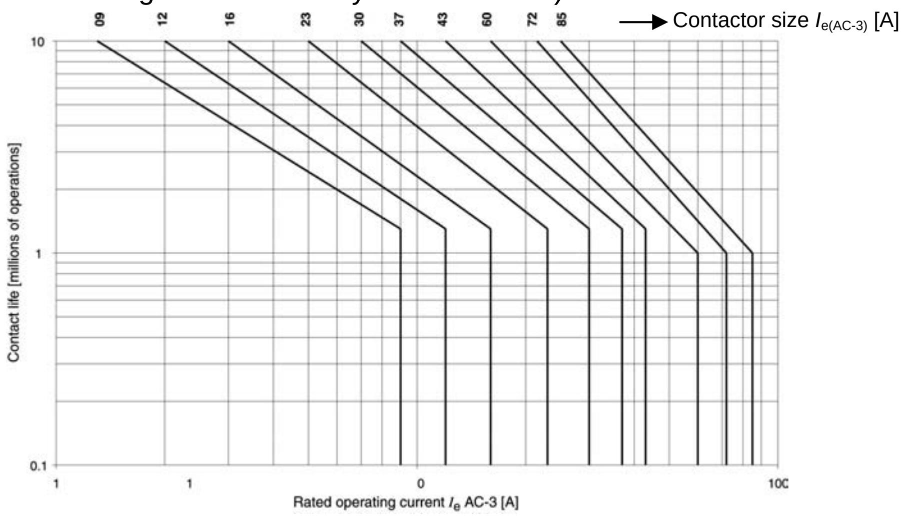


Fig. 2.3-7
Example of a diagram for determining the electrical life span of contactors as a function of the rated operational current I_e for utilization category AC-3.
The diagram applies up to 460 V, 50/60 Hz.

Example

Background:

Squirrel-cage induction motor 7.5 kW, 400 V, 15.5 A, AC-3 (switching off only when running), operating cycle 2 minutes ON / 2 minutes OFF, 3-shift operation, expected service life 8 years.

Objective:

Selection of the contactor

Solution:
2 min ON + 2 min OFF = 15 switching operations/h. This results for 3-shift operation over 8 years in around 1 million switching operations.

From diagram **Fig. 2.3-7** yields for a rated operational current of 15.5 A and 1 million required switching operations the contactor C16 (electrical life span approx. 1.3 million switching operations).

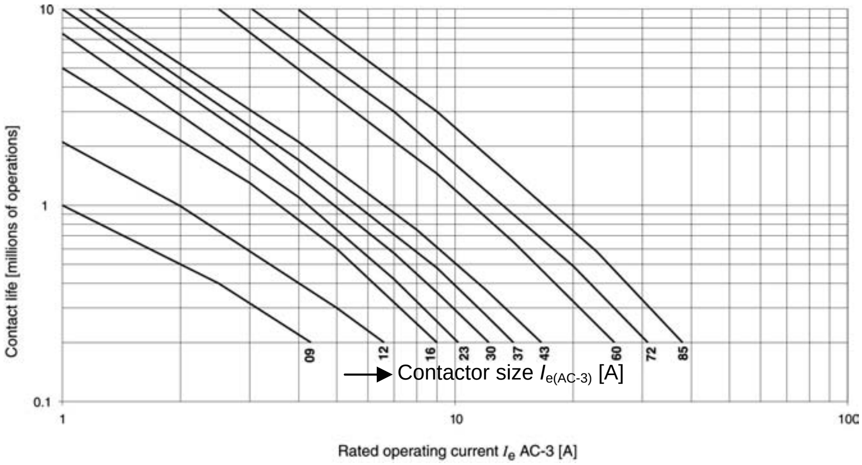


Fig. 2.3-8
Example of a diagram for determining the electrical life span of contactors as a function of the rated operational current I_e for utilization category AC-4.
The diagram applies up to U_e=690 V, 50/60 Hz.

Example

Background:

Squirrel-cage induction motor 15 kW, 400 V, 29 A, plugging, switching off rotor at standstill at $I_A = 6 \cdot I_e$, expected life span = 0.2 million switching operations.

Objective:

Rating of starting and braking contactors.

Solution:

The starting contactor (circuit making only) is selected according to the maximum permitted rated power at AC-3 (see **Fig. 2.3-7**): C30.

The brake contactor is selected according to the maximum permitted rated operational power at AC-4 and 0.2 million switching operations according to Diagram **Fig. 2.3-8**: C72.

For mixed service, i.e. service of the contactor with AC-3 and AC-4 switching operations, the life span results from the sum of the loadings. In the catalogs, diagrams for certain %-rates of AC-4 operations, for example 10 %, are provided. The RALVET electronic documentation is available for determining the life span for other percentage rates, or direct inquires must be made.

If in practice the electrical life span was considerably shorter than desired, there are several possible causes and explanations:

- More switching operations than expected, e.g. operated by extremely sensitive controller.
- More frequent inching than expected, e.g. unskilled operation.
- Permitted frequency of operation exceeded, e.g. chattering contacts
- Short-circuits, e.g. switching pause too short for reversing or star-delta starters.
- Synchronization with the supply voltage. Semiconductors as controllers could for example always switch off at the same phase angle and act in the same direction of current-flow (results in one-sided material migration to the contacts like in direct current control).

Assessment of the contacts

In conjunction with the electrical life span, the question often arises of assessment of contacts after a certain service period for continued serviceability. At least with large contactors, the contacts can be inspected.

Already after the first few switching operations, there are clear signs of burn-off on the contact surface. After a relatively small number of switching operations, the entire contact surface becomes roughened and blackened. Black deposits and traces of arc extinction can be seen on the surrounding components. Serrated edges and loss of contact material toward the arcing chamber are also normal.

The end of the contact life span is really reached when larger areas of the contact plating have broken off or there is a danger of the contact touching the substrate material. The below figures are intended as an aid for an assessment of contacts.

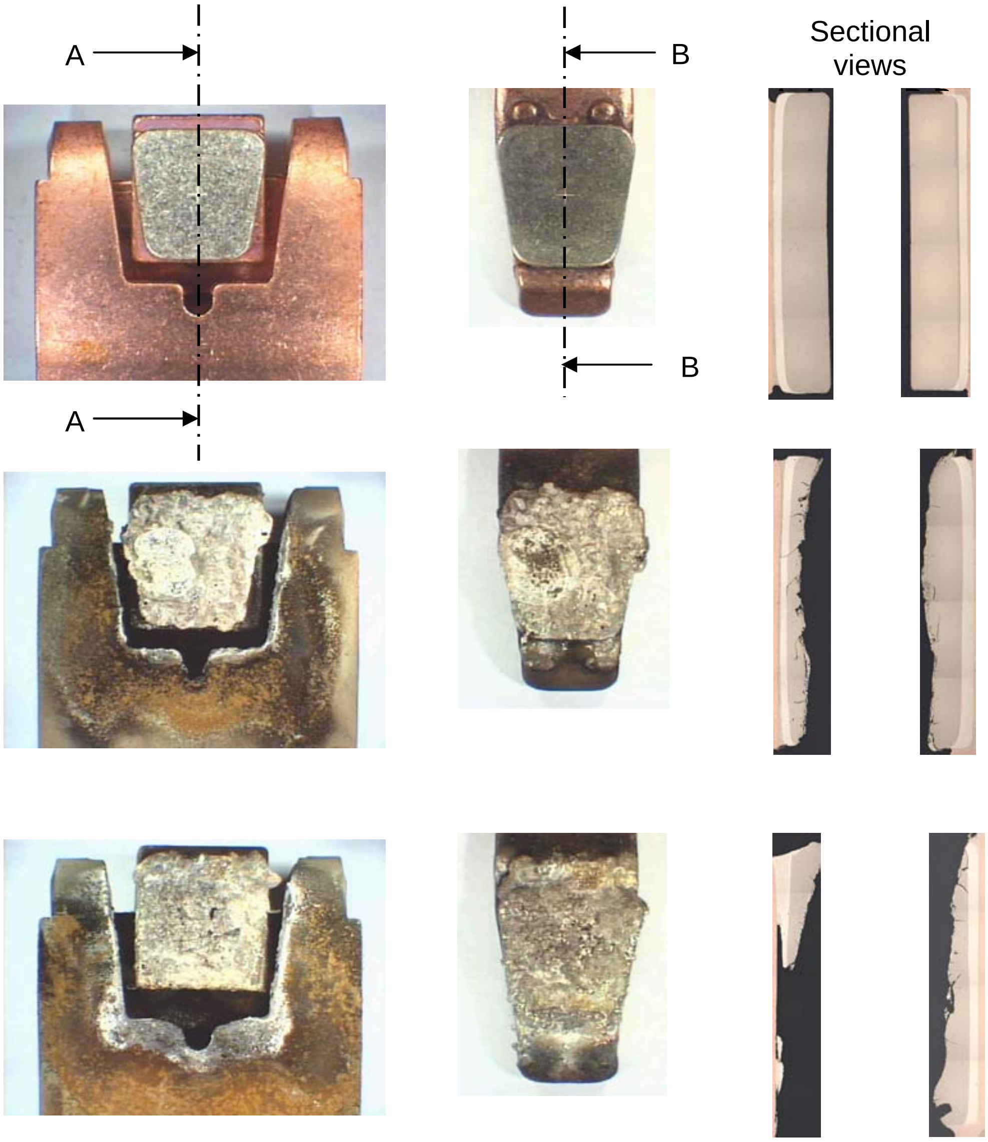


Fig. 2.3-9
Contacts of a power contactor at various stages of the life span with AC-3 loading
Fig.s above: Contacts in new state
Fig.s in center: Contacts after approx. 75 % of the electrical life span; Contact material partially eroded; contacts still operable
Fig.s below: Contacts at the end of their life span; Substrate material visible, contact material eroded down to the substrate; further use would lead to contact welding and excessive temperature rise.
The pictures on the right show the contact state in long section. The images of the various life span phases originate from various contacts, as the contacts can no longer be used once the section has been cut.

2.3.7 Intermittent and short-time duty, permissible frequency of operation

With continuous duty, i.e. with constant loading over hours, days and longer, the switchgear reaches its thermal equilibrium. The individual components reach their steady-state temperatures. The rated loading values refer from a thermal view point to continuous duty at a certain ambient temperature (see Section **2.3.5**). IEC 60034-1 defines the continuous duty of motors at the rated operational current until the steady-state temperature is reached as the rated service type S1.

In practice in addition to the continuous duty there is a large number of loading situations with changing loads. In intermittent operation, load-phases and de-energized breaks alternate in regular sequences. The load periods and intervals are so short that the components of the switchgear (and of the load) do not reach their thermal equilibrium neither during the warming nor the cooling phases. For motors the three rated service types S3, S4 and S5 are defined for intermittent operation in IEC 60034-1 (S3…constant load; S4…with additional starting load; S5…with additional starting and braking load).

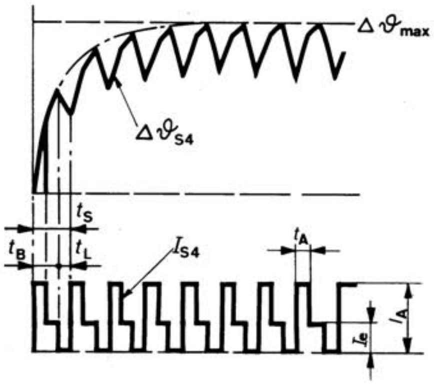


Fig. 2.3-10
Current loading and temperature rise during intermittent duty
I_{S4} Current loading during intermittent duty S4
$\Delta\delta_{S4}$ Heating and cooling during intermittent duty S4
For meaning of other symbols see ***Fig. 2.3-11***

In short-time duty the current flows for a limited time so that steady-state temperature is not reached. The de-energized interval after the load-period is however so long that the devices can nearly cool down to the ambient temperature. In IEC 60034-1 the short-time duty for motors is named rated service type S2.

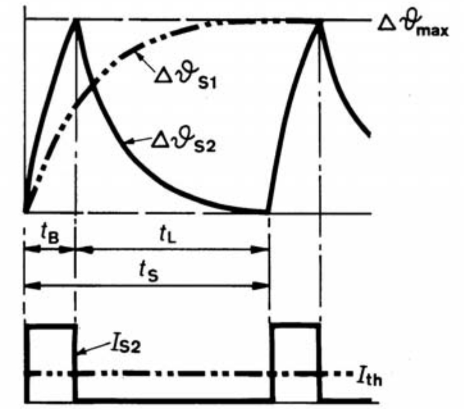


Fig. 2.3-11
Current loading and temperature rise in short-time duty S2
t_B Load duration
t_L De-energized interval
t_S Duration of a switching cycle
I_{th} Thermal continuous current
I_{S2} Current loading with short-time duty
$\Delta\delta_{max}$ Maximum permissible temperature rise
$\Delta\delta_{S1}$ Temperature rise with thermal continuous current
$\Delta\delta_{S2}$ Heating and cooling with short-time duty
Comment: In short-time duty a higher temperature than in continuous duty is permitted!

With intermittent or short-time duty, the loading current can be higher than in continuous duty, without resulting in the permitted temperature being exceeded. Therefore, for example, for switching ohmic loads and rotor contactors for slip-ring motors smaller contactors can be selected than would be required according to the rated current of the load.

When switching squirrel-cage induction motors, transformers, capacitors and incandescent lamps, the required contact rating is however the main selection criterion. The size of contactors for these applications is therefore determined by the rated operational current and the respective utilization category for all service types.

2.3.7.1 Intermittent duty and relative ON-time

In order to define a specific intermittent duty, in addition to the value of the current either the load and cycle time or the frequency of operation per hour together with the relative ON-time are preferably stated.

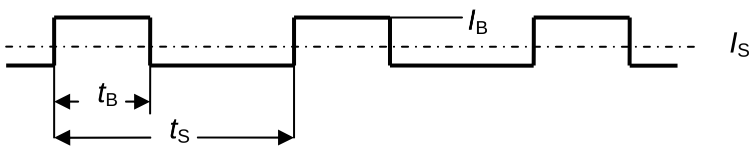


Fig. 2.3-12
Intermittent duty

$$I_S = I_B \cdot \sqrt{\frac{t_B}{t_S}}$$

I_S	*Average current loading (r.m.s. value during a switching cycle and hence also during the whole service time) [A]*
I_B	*Current during period under load [A]*
t_B	*Load duration [s]*
t_S	*Switching cycle = load duration + de-energized interval [s]*
ED	*relative ON-time = t_B/t_S [%]*

The relative ON-time – usually expressed as a percentage – is the ratio of the load duration to the cycle-time, whereby the cycle-time is the sum of the load duration and the de-energized interval.

The average current loading I_S must always be somewhat lower than the thermal continuous current, so that the temperature rise peaks at the end of each period under load do not exceed the permitted values. With stator contactors of slip-ring motors, especially with short switching cycles, the higher current during the starting time (see **Fig. 2.3-10**) as well as the additional heating effect of the electric arcs must be taken into account.

At high frequency of operation the heating effect of the starting current and the switching arc is greater than the cooling effect of the de-energized intervals so that contactors with higher ratings must be chosen than would normally be required according to the rated operational current. The selection is made based on the graphs for the permissible frequency of operation.

Even without electrical loading, the frequency of operation of contactors is limited by the maximum permissible temperature of the coil or the electronic coil control circuit, if any. The in-rush currents of the coil (**Fig. 2.3-13**) make a considerable contribution at higher frequencies of operation to the overall heating of the coil and of the contactor. This applies both for alternating current and for direct current magnets with series resistance or contactors with double-winding-coils (economy circuit) and also to electronic coil control circuits.

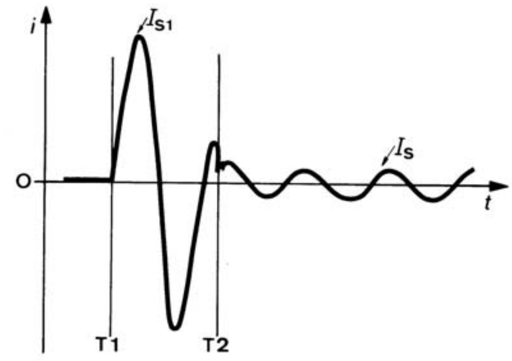


Fig. 2.3-13
Coil current at closing a contactor a.c. magnet
I_S Rated current of coil
I_{S1} Inrush current of coil (depending on contactor 6... 15 · I_S)
T1 ON-command (coil circuit closed)
T2 Magnet closed

The permissible frequency of operation of conventional coils can be exceeded short-time without risk, as the time constants for the heating of coils is 5 to 20 minutes depending on contactor size.

True direct current magnets do not exhibit in-rush currents. Therefore with these the ON and OFF delay times, which in this case are notably longer, determine the maximum frequency of operation.

With electronically controlled coils, the permissible frequency of operation is determined by the thermal load capacity of the electronic components and may not be exceeded.

With electrical loading, the temperature rise of the contacts must also be taken into account for determining the permissible frequency of operation. Although, heat is dissipated during the de-energized intervals, the contacts are additionally heated to a considerable degree by arcing and by the starting currents when switching motors. The permissible frequency of operation is therefore dependent on the relative ON-time, the size and duration of the motor starting current and on the breaking current. Corresponding diagrams are provided in the catalogs for typical applications (**Fig. 2.3-14**).

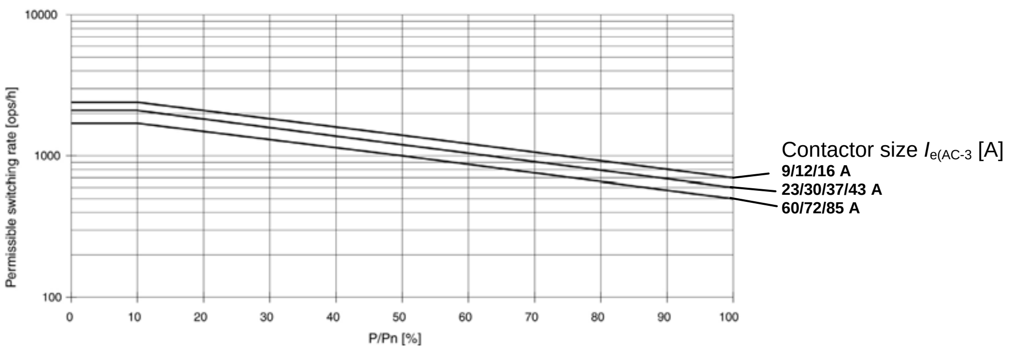


Fig. 2.3-14
Example of a frequency of operation characteristic for contactors. The frequency of operation for small loads is limited by the temperature rise of the coil.

At higher frequencies of operation, the contacts are predominantly loaded by the starting currents. This also applies to motor windings.

When switching motors – assuming that the motor is correctly rated for the stated frequency of operation – it should be checked whether the overload protection device is suitable for the high frequency of operation and that it does not release early or late. See also Section **4.1.2**.

Note

Inadvertently exceeding of the permissible frequency of operation is the most frequent cause of prematurely eroded contactor contacts. If the contactors are made to “chatter” by rapidly recurring interruptions of the coil current and at the same time switch high currents – e.g. starting currents of motors – this results in heavy wear that can lead to welding or destruction of the contacts.

It is often difficult to identify faults in switching circuits as they can have a variety of causes, for example:

- Loose terminals
- Gradually opening contacts of thermostats, pressure sensors, limit switches etc.
- Strongly bouncing control contact
- Slowly activated control switch
- Incorrectly programmed PLC
- Drop of control voltage

2.3.8 Rated frequency and harmonics

See also Section **2.4.3**.

The normal supply frequencies for all catalog data are 50 and 60 Hz. Also for direct current applications corresponding values are provided in the technical data. With other frequencies, whether higher (for example 400 Hz in military and aviation applications) or lower (for example 16 2/3 Hz on railroads) the loading of switching and protective devices changes. An examination of the suitability for the respective application and the determination of the performance data for the specified loadings are essential prerequisites for correct device selection.

Also in applications in which harmonic contents of the current occur – for example in variable speed drives – the performance data of switching and protective devices may be affected.

2.3.9 Safety clearances

For devices that generate electric arcs, especially for circuit breakers, safety clearances to adjacent devices, conductors or conductive surfaces may be required, as the arc gases (plasma) can be ejected with very high temperature and speed. The safety clearances specified in the manufacturer documentations must be observed to avoid risks to persons and equipment. If the required safety clearances are not observed a secondary short-circuit may be created on the input side of a circuit breaker – for example when conductive gas is emitted during switching off a short-circuit. Such short-circuit would be switched off by the next short-circuit protective device on the supply side, whose rated current usually would be significantly higher. The destructive energy of the electric arc and the danger to persons and material are correspondingly high.

The safety clearances are usually stated in the dimensional drawings for the devices (see example **Fig. 2.3-15**).

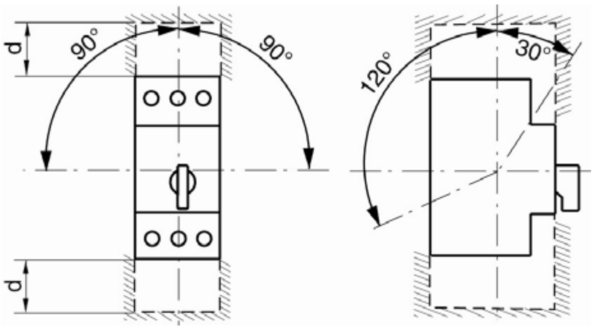


Fig. 2.3-15
Example of a dimensional drawing stating the required safety clearances to conductive materials; the safety clearances do not apply to connected, insulated conductors

Clearances between devices may also be necessary from a thermal viewpoint, in order to ensure adequate heatflow and compliance with the operationally permissible temperatures. These specifications are also available in the catalogs or on request. See also Section **6.1**.

2.3.10 Mounting position

Certain electrical devices such as contactors and circuit breakers may be subject to restrictions with respect to the permissible mounting position (**Fig. 2.3-16**) or their operational parameters may change with the mounting position. Thus standing contactors (table-mounted), if this mounting type is permissible at all, typically exhibit longer dropout times and are sensitive to impacts in vertical direction. Suspended contactors (overhead position) may require higher pull-in voltages, which pushes the lower limit of the tolerance range of the control voltage upward.

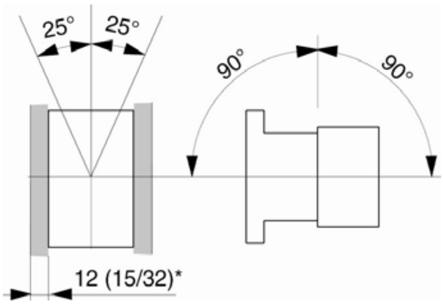


Fig. 2.3-16
Permissible mounting position of a contactor (example).
The gray zone on the side indicates the required clearance from grounded components.

Specifications on the permissible mounting positions can be found in the dimensional drawings of the devices. With respect to the influence on the operational parameters of installation in positions that differ from the standard position (suspended, upright), it is recommended to inquire directly to the manufacturer.

2.3.11 Protective separation

For protection against electric shock in conjunction with the use of electronic control devices, protection by SELV (Safety Extra Low Voltage) and PELV (Protective Extra Low Voltage) is increasingly being chosen. The maximum voltage levels for SELV and PELV are 50 V a.c. and 120 V d.c. (with exception of special applications with lower limit values).

In circuits with SELV and PELV, all devices that are included in the circuit must be isolated from other power circuits by insulation corresponding to that of a safety transformer. That means double creepage distances and the next higher impulse voltage withstand level U_{imp}. This applies for example for auxiliary circuits of switchgear with respect to their power circuits (**Fig. 2.3-17**).

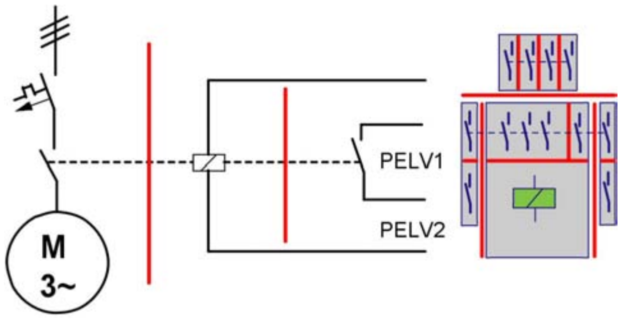


Fig. 2.3-17
Protective separation between power and control circuits

This is usually achieved by a reduction in the rated operational voltage. This means that for example a contactor suitable for 690 V can be used at 400 V in SELV and PELV circuits. The approval of SELV and PELV circuits requires design features that guarantee that protective separation is maintained even in the event of faults (for example broken parts). When selecting switchgear for SELV and PELV circuits attention must be expressly paid to the declaration of protective separation at the respective operational voltage.

2.3.12 Site altitude

The site altitude and hence the air density play a role with respect to the cooling conditions, the dielectric withstand voltage and electric arc extinction. A site altitude of up to 2000 m is considered as normal in accordance with IEC 60947. For higher altitudes, some performance data of the devices must be reduced. With power electronics devices in many cases load reductions already apply from 1000 m. In the product catalogs specifications should be found about the site altitudes on which the performance data is based.

For contactors, bimetallic thermal overload relays and circuit breakers with bimetallic tripping mechanisms, approximate values for the reduction of ratings at altitudes above 2000 m are provided in **Tab. 2.3-6**.

Altitude above sea level		[m] [ft]	2000 6600	3000 10000	4000 13000	5000 16500
Contactors						
Reduction factor for $I_{AC\text{-}1}$		$n \cdot I_e$	1.0	0.95	0.9	0.85
Reduction factor for $I_{AC\text{-}2}$, $I_{AC\text{-}3}$, $I_{AC\text{-}4}$	up to 415 V	$n \cdot I_e$	1.0	0.95	0.9	0.85
	up to 500 V	$n \cdot I_e$	1.0	0.93	0.85	0.78
	up to 690 V	$n \cdot I_e$	1.0	0.87	0.77	0.65
Bimetal overload relays 1)						
Adjustment factor on the rated operational current of the motor 2)		$n \cdot I_e$	1.0	1.06	1.11	1.18

1) Also applies for circuit breakers with bimetal tripping mechanisms. The trip characteristics of electronic protective relays usually do not change with the site altitude
2) Reduction of the rated operational currents of motors in relation to the site altitude in accordance with specifications of the motor manufacturer to be considered additionally

Tab. 2.3-6
Correction factors for applications at altitudes over 2000 m

2.3.13 Shock and vibration

Low-voltage switchgear is designed and tested for loading by shock and vibration for normal industrial usage. This includes the usual stress in operation, for example, as a consequence of vibrations during switching of contactors.

In applications with increased stress by shock and vibration such as for example in vehicles, in rail transport or on ships a variety of measures is required to protect the devices from the immediate influence of externally generated shock and vibrations. In the simplest case, by optimization of the mounting position. In case of doubt, the manufacturer should be consulted.

2.4 Specific application conditions and switching tasks

2.4.1 Parallel and series connection of poles

2.4.1.1 Parallelling

Parallel connection of poles in switchgear increases its thermal load capacity. It should be remembered that the resistances of the individual poles vary due to contact burn-off, deposits etc. The current does not distribute itself equally among the parallel poles, but corresponding to their particular impedances.

A reduction factor for the total load must be applied to avoid overloading of the individual contacts. In practice the following values for the permissible total current can be calculated with:

- with 2 parallel poles $I_{e2} = 1.8 \times I_e$
- with 3 parallel poles $I_{e3} = 2.5 \times I_e$

The making and breaking capacity remain in parallel circuits the same as for single contacts , as frequently one contact is opening or closing first and therefore must take the largest part of the switching work. Therefore it is not possible to increase the contact rating of contactors for switching motors and capacitive loads by parallel connection of contacts. **Tab. 2.4-1** shows the switching capacity based on the total current with 2 and 3 contacts connected in parallel.

	Three pole switching → I_e	2 poles in parallel [1)] → $I_{e2} = 1.8 \cdot I_e$	3 poles in parallel [1)] → $I_{e3} = 2.5 \cdot I_e$
Making capacity	$12 \cdot I_e$	$(12 \cdot I_{e2})/1.8 = 6.7 \cdot I_{e2}$	$(12 \cdot I_{e3})/2.5 = 4.8 \cdot I_{e3}$
Breaking capacity	$10 \cdot I_e$	$(10 \cdot I_{e2})/1.8 = 5.6 \cdot I_{e2}$	$(10 \cdot I_{e3})/2.5 = 4 \cdot I_{e3}$
[1)] Voltage across each contact $U = U_e/\sqrt{3}$			

Tab. 2.4-1
Making and breaking capacity of contactors as a multiple of the rated operational current I_e for three pole switching and for two and three parallel poles

For this reason contactor poles should only be connected in parallel for switching resistive loads (utilization category AC-1). Where possible they should only be connected in parallel by means of copper bars fed in the center in order to ensure symmetrical current distribution and good heat dissipation. For small contactors special connecting bridges are available.

Any short-circuit currents that occur are distributed between the poles depending on the given pole resistances. In the case of circuit breakers with parallel contacts, it may happen at small short-circuit currents that the operating current of undelayed electromagnetic short-circuit releases is not reached. Consequently such a short-circuit is only switched off by the thermal release after a delay. The pick-up threshold for undelayed short-circuit breaking rises approximately by a factor given by the number of parallel poles.

2.4.1.2 Series connection

When two or three poles of switchgear are connected in series (**Fig. 2.4-1**), the advantages include the following:

- Increased dielectric withstand voltage
- Improved switching capacity
- Higher operating voltage
- Larger contact life span

These advantages are exploited by using three-pole contactors and circuit breakers for switching single-phase alternating current and above all direct current. The limit for higher operating voltage is determined by the rated insulation voltage that may in no event be exceeded. The permissible current loading of poles connected in series is the same as for individual poles.

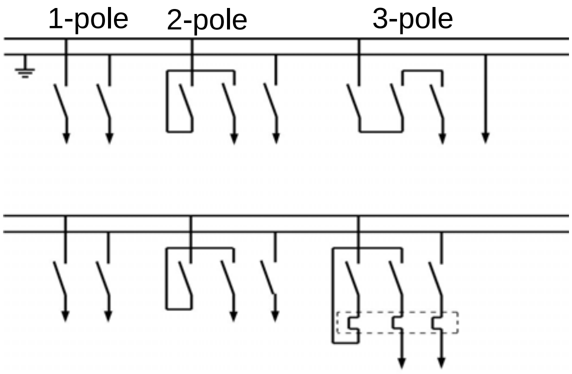


Fig. 2.4-1
Examples of diagrams for poles connected in series. Where grounded power supplies are used (top graph) with loads switched on both sides, it should be noted that ground faults can lead to bridging of contacts and hence to a reduction in the breakable voltage.

The overload trip characteristics of devices with thermally delayed bimetal tripping mechanisms, such as circuit breakers and overload relays, apply when all three bimetal strips are equally loaded. This is guaranteed by connecting the circuits in series. In devices that are sensitive to phase failure, series connection of all circuits is compulsory. With electronic motor protection relays, it may be necessary to deactivate the phase failure protection.

The impact of series connection of circuits when switching direct currents is dealt with in Section **2.4.2**.

For the effect of series connection of circuits on switching frequencies < 50 Hz and > 60 Hz see Section **2.4.3**.

2.4.2 AC switchgear in DC applications

Switchgear designed for alternating current can carry at least the same rated continuous operational DC current. With direct current the skin effect in the circuits disappears and none of the specific effects associated with alternating currents such as hysteresis or eddy current losses occur.

DC devices that are operated at low voltage can be switched by AC switchgear without difficulty, as their direct current switching capacity at low voltages is practically the same as for alternating current.

With voltages in excess of around 60 V, the direct current switching capacity of AC switchgear with double-breaking contacts (for example contactors) decreases strongly. By connecting two or three circuits in series (**Fig. 2.4-1**) this limit can be raised to twice or three times the voltage.

The reason for the reduced switching capacity with DC compared with AC is the absence of the current zero crossover that with AC supports the quenching of the electric arc. The electric arc in the contact system can continue to burn under larger direct voltages and thus destroy the switchgear. With direct voltages, the contact erosion and hence also the contact life span differ from those at alternating voltage. The attainable values for direct current are specifically tested and documented.

With direct current, the load affects the switching capacity more strongly than with alternating current. The energy stored in the inductance of the load must largely be dissipated in the form of an electric arc. Hence with a strongly inductive load (large time constant L/R) the permissible switching capacity for the same electrical life span is smaller than with an ohmic load due to the much longer breaking times.

Overload release units

The reaction of bimetal strips heated by the operating current depends on the heat generated in the bimetal strips and in their heating coil, if any. This applies equally for alternating current and direct current. The trip characteristic can be somewhat slower with direct current as there are no hysteresis and eddy current losses. With overload releases that are sensitive to phase failure, all three circuits should always be connected in series to prevent premature tripping.

Overload releases heated via current transformers are not suitable for direct current. Also electronic overload relays in most cases cannot be used in direct current applications as the current is measured via current transformers and their functionality is tailored to alternating current.

Short-circuit releases

Electromagnetic overcurrent releases can be used with direct current. However the tripping threshold current is somewhat higher than with alternating current.

Undervoltage and shunt-trip releases

Undervoltage and shunt-trip releases operate with magnet circuits. Special designs are required for direct voltage.

2.4.3 Applications at supply frequencies < 50 Hz and > 60 Hz. Effect of harmonics

Low-voltage switchgear is designed for a supply frequency of 50 ... 60 Hz. If it is desired to use them for other rated frequencies the following device characteristics should be checked:

- thermal load capacity of the circuits,
- switching capacity,
- life span of the contact system,
- release characteristics,
- operating characteristics of magnetic and motor drives.

The effect of higher frequencies on the performance of low-voltage devices should be considered both in networks with higher basic frequencies (for example 400 Hz) and also in cases where current-harmonics occur. Such current-harmonics occur if the supply voltage contains harmonics or if non-linear consumers are connected. Such consumers may for example be compensation devices for luminescent lamps that operate in the range of saturation or devices with phase angle control. With consumers with phase angle control and with frequency converters (Inverters; see Section **3.10**) harmonics with frequencies up to several kHz may arise in the supply. The harmonic content can be increased by capacitors connected to the supply, whose current consumption increases with increasing frequency. Special attention should be paid to this factor in individually compensated motors and a correction of the current settings of the protective relay may be required.

In applications in which current-harmonics arise, the effect of the harmonics (for example additional heating effects) is added to that of the basic frequency. This can be especially critical in devices that contain coils or ferromagnetic materials (bimetal heating coils, magnetic releases etc.).

In the case of loads with connection to the neutral conductor (e.g. single-phase loads such as luminescent lamps, small power adapters etc.), a high harmonic content can result because of the formation of a zero-sequence-system that may lead to thermal overloading. This should also be taken into account in the use of 4-pole switchgear.

2.4.3.1 Effect of the supply frequency on the thermal load

In contrast to direct current, with AC the current does not flow evenly through the cross-section of a conductor. The current density falls from the surface inward. This effect – known as the skin effect – increases with increasing frequency so that at very high frequencies the core of the conductor is virtually de-energized and the current only flows in a relatively thin layer at the conductor surface.

This means that with increasing frequency, the resistance of the circuit increases. In addition, due to magnetic induction, higher hysteresis and eddy current losses are created in adjacent metal parts. Especially ferromagnetic materials (arc extinguishing parts, screws, cage terminals, magnets, base plates) can reach unacceptably high temperatures. Special care should be taken at frequencies > 400 Hz.

Because of the variable cross-sections of the conductive parts as well as the different nature and distances to adjacent metal parts, additional heating effects and especially the local overtemperatures vary according to device type. This has the following consequences for the load capacity of the switchgear and the switchgear combinations.

Individual clarification is required for each individual application as a general statement cannot be provided due to the widely differing design features, especially at frequencies > 400 Hz.

Load capacity of contactors, load switches and circuit breakers

Devices that are designed for a frequency of 50/60 Hz can, from a thermal viewpoint, be used for the same rated current at a lower frequency. Approximate values for permissible operational currents are stated in **Fig. 2.4-2**. The actual reduction factors vary according to design and the rated current range of the devices. It should be noted that cage-type terminals have an adverse effect on heating at higher frequencies.

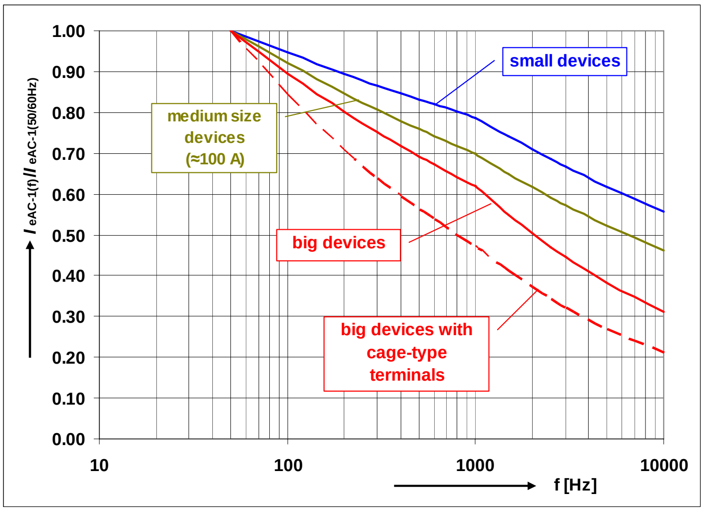


Fig. 2.4-2
Approximate values for permissible operational currents AC-1 of contactors, load switches and circuit breakers at higher frequencies relative to I_e at 50…60 Hz

Higher frequencies and installation provisions

For installation at higher frequencies, special attention must be paid to the effects of current distribution (skin effect), hysteresis and eddy current losses:
The conductors to be connected should be rated according to the higher frequency (larger cross-section, flat or tube conductors). The load capacity of circuits at higher frequencies can be roughly estimated by help of **Fig. 2.4-3**. It depends on the geometry of the rails and their arrangement and should be measured separately in each individual case. The conductors should be positioned as far as possible from conductive (especially ferromagnetic) parts, to minimize inductive effects.

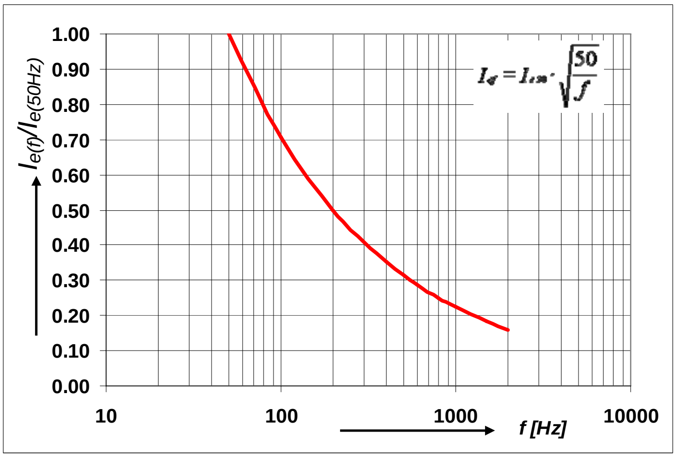


Fig. 2.4-3
Approximate load capacity of busbars at higher frequencies [12]
I_{e50} Load capacity at 50 Hz
I_{ef} Load capacity at frequency f

In order to reduce losses, no cage-type terminals should be used. This is especially important with currents > 100 A!
For single phase loads over 400 Hz, the two outer poles of contactors should be used in parallel for the feed line and the middle pole for the return line. This results in a partial mutual compensation of the magnetic induction.

2.4.3.2 Effect of the supply frequency on the switching capacity

The starting currents of motors for higher frequencies are sometimes higher than those at 50/60 Hz. At 200 Hz this can result in 15 times the rated current and at 400 Hz up to 20 times. The power factor may be significantly worse than for motors at 50/60 Hz. Allowance should be made for the increased making currents when selecting devices.

Switching capacity of contactors and load switches

When breaking a.c. circuits, the clearance between open contacts must be sufficiently de-ionized during the current zero crossover to prevent a re-ignition of the electric arc in the next half cycle. At higher frequencies, the increase of the voltage after the zero crossover is usually faster. The electric arc duration per half cycle and hence the ionization of the distance between open contacts is however smaller. Therefore contactors and load switches (zero-point interrupters) up to around 400 Hz have virtually the same switching capacity as at 50/60 Hz.

Insofar as the making currents are permissible (see above) – a reduction of the rated current I_e according to **Fig. 2.4-2** for contactors and load switches is only required because of the larger thermal loading at higher frequencies.

The circumstances at lower frequencies are less favorable. The effect of the strong ionization of the switching chamber due to the longer presence of the electric arc is predominant with non current limiting switchgear. The switching capacity falls at lower frequencies and becomes more heavily dependent on the voltage and the inductance of the load.

The full rated operational current for three-pole operation at 400V and 50/60 Hz can be permitted at 16 2/3 Hz and 400 V with two poles in series. For rated operational voltages up to 500 V and 16 2/3 Hz all poles should be connected in series so that the full rated operational current can be operated.

At frequencies below 16 2/3 Hz, the direct current switching capacity of switchgear in accordance with catalog specifications must be applied.

Switching capacity of circuit breakers

The short-circuit currents in medium frequency supplies are comparatively low. Any reduction of the switching capacities at frequencies over 400 Hz compared to 50/60 Hz does therefore not cause problems in practice.

The effect of the current limitation is reduced with increasing frequency, as at higher frequencies the peak value of the short-circuit current is already reached during the reaction time of the switch. In view of the comparatively low short-circuit currents in medium frequency supplies, this is not relevant in practice. The short breaking times of current limiting circuit breakers are retained.

With two poles connected in series, circuit breakers with current limitation in single-phase supplies typically reach up to 400 V the rated breaking capacity at 50/60 Hz. At voltages over 400 V to 690 V a.c. on the other hand, series connection of three poles is required. In single-phase supplies it must always be ensured that all three poles of thermally delayed overload releases are in the current loop.

2.4.3.3 Performance of release units at supply frequencies < 50 Hz and > 60 Hz

Thermal overload releases

Thermally (current-dependent) delayed overload releases and relays operate with bimetal strips. These are usually heated via a heating coil by the heat losses of the operating current or the secondary current of a current transformer.

Up to around 400 Hz, the heat losses in the heating coils (ohmic losses) are the main heat source. The additional inductive heating in the bimetal strips itself is practically negligible up to these frequencies, so that the tripping characteristic will only be slightly faster than at 50 Hz. At frequencies over 400 Hz the proportion of inductive heating increases and the ultimate tripping current falls with increasing frequency.

Overload relays that are connected to main current transformers with a high overcurrent factor (protective current transformer) or that have integrated current transformers, display a somewhat faster tripping characteristic in comparison to 50 Hz at frequencies over 50 Hz to 400 Hz.

The trip characteristic of relays with a saturation current transformer for heavy-duty starting becomes considerably faster with frequency increasing up to 400 Hz as the saturation effect will move proportionally to the frequency towards higher currents.

Electronic overload devices

Due to the variety of principles of operation, no general statement can be made on the performance of electronic overload relays at frequencies over and below 50/60 Hz. With relays with current transformers it should be noted that application at low frequencies is limited because of transformer saturation.

Short-circuit releases

For the activation of electromagnetic overcurrent releases, in addition to the size of the current also the time is relevant during which the current is applied. At 50/60 Hz the armatures of the electromagnetic overcurrent releases are activated within around 5 ms. During the half-cycle, the force is sufficient to pull the armature all the way through to its end position. At higher frequencies the duration of a half cycle is too short.

The pick-up-threshold of the short-circuit-releases increases over 50/60 Hz and at around 400 Hz approaches 1.4 times of the 50/60 Hz value.

Increased operating frequencies can lead to increased temperature-rise of the releases.

2.4.3.4 Switchgear used with soft starters

Overload protection

Thermal relays and circuit breakers are equipped with thermal overcurrent releases that can be adjusted to the motor rated current and even during soft starting map the motor heating. The harmonic components of the currents that also contribute to motor heating are measured.

The performance of electronic motor protective devices with respect to the effect of the harmonics (for example true r.m.s. value measurements) should be obtained from the respective device documents.

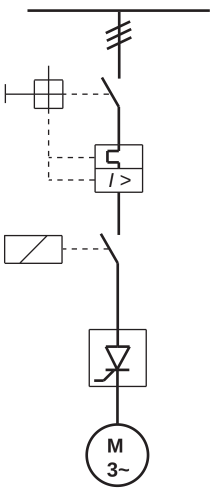


Fig. 2.4-4
The basic design of a power circuit with circuit breaker, contactor and soft starter

Installations that allow heavy-duty starting via a soft starter with a starting time of around 1 minute and longer require besides a specifically selected motor also specifically selected switching and protective devices.

It is a good idea to protect motors for heavy-duty starting that are activated by soft starters with electronic motor protective devices. The circuit breaker must be selected and adjusted so that it does not trip before the motor protective device and that it is thermally capable for the specific load (harmonics content and starting time). Circuit breakers without thermal releases can be employed to advantage. The selection and adjustment of the circuit breaker is as for heavy-duty starting conditions (see Section **4.1.2.2**). In this case, the circuit breaker only has to provide short-circuit protection and/or line protection.

Short-circuit protection

Short-circuits are critical and endanger the power semiconductors of the soft starters. Circuit breakers are not sufficiently fast to protect power semiconductors of soft starters against short-circuits. For short-circuit protection, the specifications provided by the soft starter manufacturer should therefore be observed. Short-circuit protection for the power semiconductors of soft starters is often omitted for cost reasons, whereby such coordination only satisfies the requirements of coordination type 1.

2.4.3.5 Switchgear for use with frequency converters (inverters)

Overload protection on supply side

See also Section **3.10.4**

Motors that are controlled by an inverter are not directly connected to the power supply (via rectifier, intermediate circuit and inverter, **Fig. 2.4-5**). Circuit breakers or motor protective devices upstream of the inverter do not receive any direct information about the condition of the motor and thus cannot fulfill the motor protection function. Motor protection functions are usually integrated in the inverter.

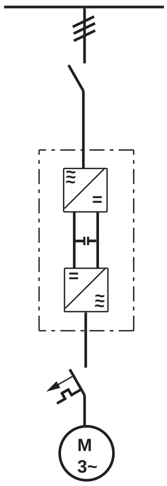


Fig. 2.4-5
The basic design of a circuit with rectifier, intermediate circuit and converter of the inverter. Frequently filters are provided on the input side (whether internally or externally) to reduce supply interference.

As the reactive current of the motor is provided by the intermediate circuit capacitance, the supply current is smaller than the motor current and its power factor cos φ is nearly 1. Because of the harmonic content of the current, the thermal overcurrent release of the circuit breaker should be set to approx. to 1.2 times the motor rated current, but no more than the permissible current carrying capacity of the connecting cable.

Short-circuit protection

Inverters usually protect themselves against short-circuits on the output side. Short-circuits on the supply side between pole conductors or pole conductors and ground are switched off by the upstream short-circuit protective device (circuit breaker or fuse).

Circuit breakers, motor protection relays or contactors in the output circuit of inverters

If low-voltage switchgear is installed in the output circuits of inverters, this must be compatible with the high switching frequency of the output signal of several thousand Hz. The harmonic content of the current can result in overheating of the devices. Especially in circuit breakers with plunger-operated magnetic releases, the sensitivity to current harmonics increases with decreasing rated current. As a guideline can serve: Due to the large number of windings on plunger coils, excessive heating should be expected with versions with < 10 A rated current. The manufacturers' specifications should be observed.

With long screened lines between the output of the frequency converter and the motor, switch contacts located between the devices can be stressed by high peak currents caused by the capacitance of the line that may even result in welding of the contacts. The high charging currents can under certain circumstances also result in undesired releasing. Filters can have similar effects. The switching mode of inverters generating steep voltage slopes can lead to additional voltage stress on long lines by traveling wave effects. Suitable filter measures may be required as a remedy.

Generally it should be ensured by the control circuit that loadside contactors are switching without load, i.e. that the frequency converters are switching on after the contactor and switching off before it.

Overload protection on the output side

Overload protective devices with bimetal strips (bimetal relays and circuit breakers with bimetal tripping mechanism) are designed for 50/60 Hz. As their mode of operation is based on the heating of the bimetal strips by the motor current, the release values relate to heating by 50/60 Hz currents. Depending on the design of the device, the switching frequencies of frequency converters extend from several kHz to the ultrasonic range and generate harmonic currents in the output that result in additional temperature rise in the bimetal strips. Long shielded lines to the motor can cause additional increases of the harmonic components because of the line capacitance.

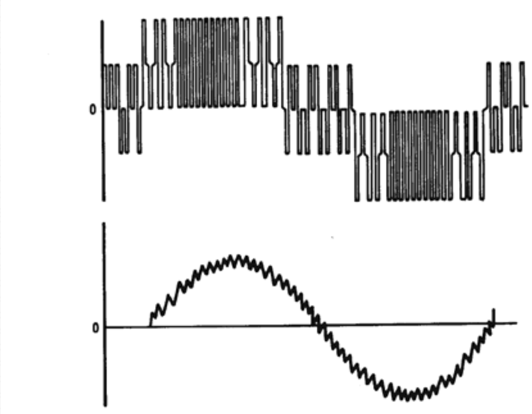


Fig. 2.4-6
The switching of the output voltage (above) results in a harmonic content of the output current of frequency converters (below) that affects the performance of protective devices on the load side.

The temperature rise is not only dependent on the r.m.s. value of the currents, but also on the induction effects of the higher frequency currents in the metal parts of the devices. The additional heating effect results in a reduction of the ultimate tripping current of the overload relays, whose extent must be individually determined for the respective combination of frequency rectifier / overload relay / connecting lines / motor. As a consequence of these effects, the current settings should be increased for overload relays with bimetals, the choice of a higher current range may even be necessary. Depending on the device combination, the factor can be up to 150 %.

As the determination of the shift of the ultimate tripping current is very time consuming in individual cases and for all possible device combinations, it is recommended in practice to set the motor protective devices by physical testing. To this end the drive with a rated load is run for around one to two hours and the overload relay initially adjusted so that there is no risk of it being released. At the end of this operating period, the current setting on the device is successively reduced until the relay trips. The final setting is around 10 % above the trip value. If interruption to operation by tripping during the test is undesired, the release contact can be temporarily bypassed. The current setting also provides the basis for checking the required size of the contactor or other switchgear in the circuit.

Also the performance of electronic overload relays may depend on and be affected by the harmonic content of inverter currents. It is not possible to make a general statement due to the differences in the modes of operation. In electronic overload relays with current transformers it should be remembered that use at low frequencies is limited because of converter saturation.

2.4.4 Application of four-pole switchgear devices

The majority of low-voltage switchgear is equipped with three contacts in the main circuit, which switch three-phase loads in all poles. In some applications switchgear with four main poles is required, either for safety reasons or for an optimum solution of the application. This may require various device configurations.

2.4.4.1 Applications of switchgear with 4 NO contacts

Four NO contacts are required or at least very advantageous for the below applications

- Applications which require the interruption of the neutral line for switching off or disconnecting loads. This can be the case in supplies with adverse grounding conditions, in TT supplies, for protective disconnection in IT or impedance-grounded networks. Attention has to be paid that the neutral pole closes before or at the same time as the other poles and opens after them or at the same time. When switching non-linear consumers, specific attention has to be paid regarding the current loading of the neutral line. See also Section **2.4.3**.

- Switching-over of supply systems (for example for standby power supplies), for which complete separation of the two supply systems is required.
- Switching of several single-phase loads (heaters, lamps) with one switchgear unit.
- Switching direct current loads with higher rated voltage that requires the series connection of four contacts (see also Section **2.4.2**).

2.4.4.2 Applications of switchgear with 2 NO and 2 NC contacts

Devices with two NO and two NC contacts are useful in applications in which one of two circuits must always be closed. These are, for example

- Switching a heater between two levels (**Fig. 2.4-7**)
- Switching-over between single-phase supplies – for example, emergency power supply systems (**Fig. 2.4-7**)
- Reversing motors for space saving arrangement of devices (**Fig. 2.4-8**)
- Reversing of 2-step motors with separated windings (**Fig. 2.4-9**)

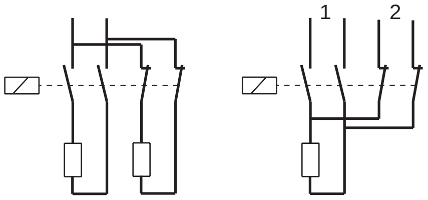


Fig. 2.4-7
Four-pole contactors with 2 NO / 2 NC contacts for switching single-phase loads (left) or switching-over between two supplies (right)

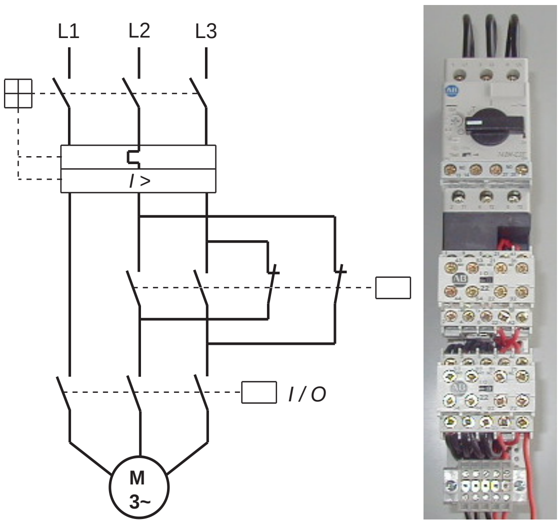


Fig. 2.4-8
Slimline reversing starter with a 2 NO / 2 NC contactor for reversing

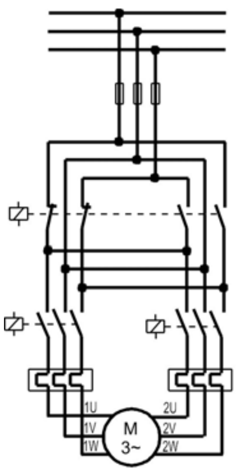


Fig. 2.4-9
Reversing of a two step motor with separate windings

2.4.4.3 Applications of switchgear with 3 NO and 1 NC contact

Devices with three NO and one NC contact are used in applications in which, when the main load is switched off – for example the motor –, another single-phase load must be switched on. Such applications could include:

- Safety circuits
- Direct current brake systems that are activated when a drive is switched off
- Clutches that must be released when the drive is switched off

2.4.5 Application of circuit breakers in IT networks

IT supplies are used to prevent that a ground fault leads to immediate disconnection of the affected circuit like in a grounded system. Although a first ground fault results in a displacement of the potential of the entire supply, continued operation is still temporarily possible. Special ground fault monitoring equipment reports any ground faults and hence makes it possible to quickly rectify the fault – often without disruption to the operation of the plant. The situation is similar in supplies with high impedance grounding.

If however a second ground fault occurs in another phase, there is a short-circuit that must be immediately cleared by the short-circuit protective device. The voltage to be switched off varies depending on the locations of the short-circuits (**Fig. 2.4-10**). This results in different voltage levels to be switched off by the short-circuit protective device and in the case of circuit breakers to different required breaking capacities.

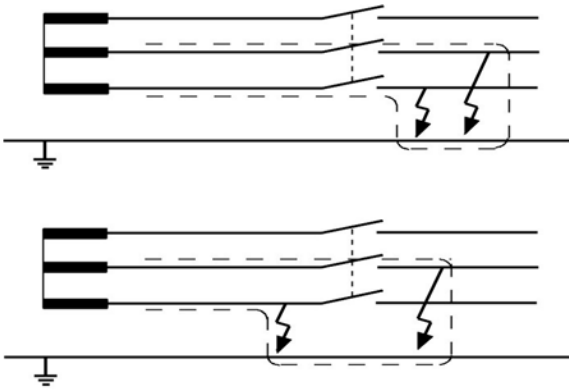


Fig. 2.4-10
Double ground faults on the load side of the circuit breakers do not cause increased stress. If, however, there is one ground fault on the supply side and the other on the load-side, a significantly higher breaking capacity is required because of the increased voltage load.

If both short-circuits occur on the load-side of the circuit breaker, the breaking work is shared between two contacts and the required breaking capacity corresponds to the normal 3-phase values.

If the location of one short-circuit is on the supply-side of the circuit breaker and the second short-circuit on the load-side, then one contact only of the circuit breaker has to perform the total breaking work and this at phase-to-phase voltage. In this case, the significantly lower single pole breaking capacity of the circuit breaker at the phase-to-phase voltage is critical. If the values cannot be obtained from the device documents, an inquiry should be made. If the short-circuit current at the installation site exceeds the single pole switching capacity of the circuit breaker, then a back-up fuse is required.

For three-pole short-circuits there is no difference between IT supplies and other supply types. The ultimate short-circuit breaking capacity I_{cu} and the service short-circuit breaking capacity I_{cs} continue to apply.

Circuit breakers under IEC 60947-2 are suitable for use in IT supplies, if they are <u>not</u> marked with the symbol . Testing is in accordance with Annex H.

2.4.6 Switchgear for safety applications

The safety of machines, systems and processes with respect to the protection of persons and property from damage of any kind is the primary objective of the legislation and of regulations and norms for technical measures and solutions. Also low-voltage switchgear is being applied in safety applications. In Section **4** "Protection" the dangers that result from electrical energy directly are dealt-with in more detail.

In safety applications it is very important to receive reliable feedback about the main contacts position so that for example it can be excluded that an auxiliary contact reports open main contacts but while in fact – for example because of contact welding – they are closed. In this context the term "mirror contacts" for power contactors is of importance. In a similar way, the methods of "positive guidance" or "mechanical link" of contacts of control contactors ensure that the position of NO and NC contacts cannot be mutually contradictory.

In modular systems, mirror and mechanically linked contacts must be mechanically fixed to the base unit, so that they cannot separate.

2.4.6.1 Mechanically linked contacts

Appendix L of IEC 60947-5-1 defines the criteria for the mechanical linking of contacts. The standard defines mechanically linked contact elements as a "combination of n Make contact element(s) and m Break contact element(s) designed in such a way that they cannot be in closed position simultaneously …". The standard also defines the test conditions: With welding of a contact – for example of a make-contact – the break-contacts of the contactor when dropped out must still have an opening clearance of 0.5 mm or withstand an impulse voltage of 2.5 kV. The same applies with welding of a break-contact.

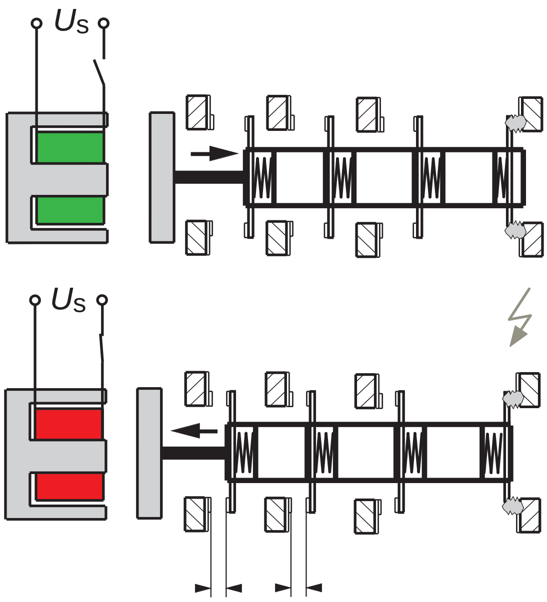


Fig. 2.4-11
The make contacts remain open when mechanically linked when the control relay is excited and a break contact has welded.

In accordance with standard, mechanically linked contacts should be clearly labeled on the device or in the documents or in both places. **Fig. 2.4-12** shows the symbols to be used.

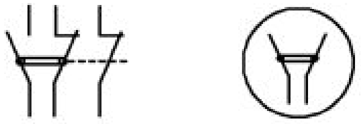


Fig. 2.4-12
Symbol for mechanically linked contacts together with contacts that are not mechanically linked (left) and symbol for mechanically linked contacts, when all contacts are mechanically linked (right)

2.4.6.2 Mirror Contacts

Appendix F of IEC 60947-4-1 defines the requirements for mirror contacts, i.e. for the unambiguous feedback of the state of the main contacts in event of fault, for example with welded main contacts. The standard defines a mirror contact as “normally closed auxiliary contact which cannot be in closed position simultaneously with the normally open main contact under conditions defined ….”, i.e. if a main contact has welded. The test conditions are similar to those for mechanically linked contacts: The auxiliary normally closed contacts that are designed as mirror contacts must still have an opening clearance of 0.5 mm or be able to withstand a test impulse voltage of 2.5 kV when the contactor is de-energized.

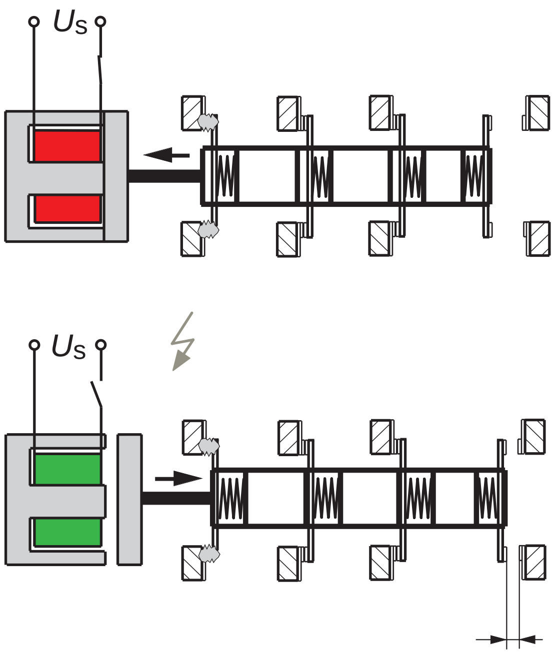


Fig. 2.4-13
Principle of mirror contacts: the normally open auxiliary contact remains open when the contactor is de-energized and a main contact has welded.

A power contactor can have several auxiliary mirror contacts. In large contactors it may be necessary to connect two mirror contacts in series, one of which is mounted on the left and the other on the right side. Thus even if the contact armature is in an inclined position – for example if an outside contact has welded – safe feedback is ensured.

Like mechanically linked contacts, mirror contacts must be marked directly on the device, in the documentation or in both locations.

Fig. 2.4-14
Symbol for marking mirror contacts

2.4.7 Installations in hazardous atmospheres

2.4.7.1 History, guidelines and regulations

The Directive 94/9/EC (ATEX 05) regulates the requirements for explosion protection in the European Union. It deals with the properties of explosion-protected devices, protective systems and components for free trade in the internal market of the EU and stipulates that the use of such devices in member states may not be prohibited, hindered or restricted.

The Directive is structured in accordance with the so-called “New Approach”. A key feature is renouncing from strict normative regulations; instead the requirements on the products are comprehensively defined directly in the directive (Appendix II: Essential health and safety requirements relating to the design and construction of equipment and protective systems intended for use in potentially explosive athmospheres). This is done in a general form, so that reference to suitable standards is normally preferable.

While placing on the market of explosion-protected devices (protective systems, components) is uniformly regulated by Directive 94/9/EC, the safe operation of these devices is ultimately regulated under national ordinances. The Directive 1999/92/EC, also known as the Safety at Work Directive, defines minimum requirements below which the requirements of the national regulations may not fall.

The extensive CENELEC standards for electrical equipment for hazardous areas apply in all West European states and practically cover the same subjects as the IEC standards.

2.4.7.2 Classification of hazardous areas

When handling combustible or oxidizing substances that are present in fine dispersion as gases, vapors, mists or dusts, risks of explosion can arise. An effective source of ignition must be present to initiate an explosion. Sources of ignition can arise in electrical plants as electrical sparks and arcs, mechanical sparks and hot surfaces.

Hazardous areas are zones, in which, due to the local and operational conditions, a potentially explosive atmosphere of a dangerous quantity can occur. Hazardous areas are classified into zones (IEC/EN 60079-10, EN 50281-3 and IEC/EN 61241-10) according to the nature of the combustible substances (gases, vapors and dusts) and according to the frequency of occurrence and duration of the explosive gas atmosphere in the Ex-zone (permanent, occasional or very seldom and short-time) (**Tab. 2.4-2**).

In accordance with Appendix I of the Directive 94/9 EC distinction is made between 2 groups of devices:

- "Equipment-group I" (Methane or combustible dusts) in the mining industry and
- "Equipment-group II" (gases or dust/air mixtures) for the remaining areas with explosive atmospheres.

"Equipment-group II" is subdivided among explosion groups IIA (for example propane), IIB (for example ethylene) and IIC (for example hydrogen). The hazard of the gases increases from explosion group IIA to IIC. The requirements on the electrical equipment increase accordingly.

Combustible gases and vapors are classified into temperature classes according to their ignition temperatures, the electrical equipment according to its surface temperature (T1 ... T6, **Tab. 2.4-4**).

As explosion-protected electrical equipment does not always have to satisfy the highest requirements, it is classified according to zone, temperature classes and the explosion group of the combustible substances. This enables the adaptation of explosion-protected electrical equipment for various ignition protection types (**Tab. 2.4-3**).

Classification of equipment acc. to IEC/EN			Categories of zones exposed to the risk of ignition	
Equipment group (application area)	Combustible substances	Equipment category	Zones IEC/EN	Temporary behaviour of combustible substances in zones exposed to the risk of explosion
I Mines	Methane, Dusts	M1	Underground parts of mines and suface installations of mines	
		M2 oder M1		
II Other areas with combustible atmospheres	Gases, vapours	**1G**	Zone **0**	Permanently, long-term or frequently present
		2G or 1G	Zone **1**	Occasionally present
		3G or 2G/1G	Zone **2**	Low probability of presence or rare occurence or short-term
	Dusts	**1D**	Zone **20**	Permanently, long-term or frequently present
		2D or 1D	Zone **21**	Occasionally present
		3D or 2/1D	Zone **22**	Low probability of presence or rare occurence or short-term

Explanation of equipment categories:
M1 Continued service in case of presence of combustible atmosphere must be guaranteed
M2 It must be possible to switch-off the equipment in case of presence of combustible atmosphere
1G/D very high safety = Equipment safety must be maintained even in case of rare malfunctions, e.g. at occurrence of two independent failures.
2G/D high safety = Equipment safety must be maintained in case of frequently expected malfunctions, e.g. in case of failure of one component.
3G/D safe under normal service conditions = Equipment safety guaranteed under normal service conditions

Tab. 2.4-2
Classification of electrical equipment according to the equipment-group (for example II) and equipment-category (for example 3 G for Zone 2) and classification by zones

Ignition protection		**Principle of protection**	**Zone**	**Standard** EN / IEC
General requirements				EN 50014 IEC 60079-0
Installation				EN 60079-14 IEC 60079-14
Flameproof enclosures	**d**	Avoid the transfer of an explosion to the outside	1 / 2	EN 50018 IEC 60079-1
Increased safety	**e**	Avoid sparks and ignition temperatures	1 / 2	EN 50019 IEC 60079-7
Intrinsic safety	**i**	Limitation of the energy of sparks and of temperatures	0 / 1 / 2	EN 50020/39 IEC 60079-11
Pressurized enclosures	**p**	Keep Ex-atmosphere away from source of ignition	1 / 2	EN 50016 IEC 60079-2
Encapsulation	**m**	Keep Ex-atmosphere away from source of ignition	1 / 2	EN 50028 IEC 60079-18
Oil immersion	**o**	Keep Ex-atmosphere away from source of ignition	1 / 2	EN 50015 IEC 60079-6
Powder filling	**q**	Avoid the transfer of an explosion to the outside	1 / 2	EN 50017 IEC 60079-5
Type of protection „n“	**n**	Various principles of protection for zone 2	2	EN 50021 IEC 60079-15
Protection by enclosure	**IP**	Keep Ex-atmosphere away from source of ignition	20 / 21 / 22	EN 50281-1-1 IEC 61241-1

Tab. 2.4-3
Ignition protection types and corresponding EN and IEC standards

The identification of ignition protection types of electrical equipment usable e.g. for *Increased Safety “e”*, Explosion Group IIC and Temperature Class T6 is different according to EN and IEC as follows (see also Section **2.4.7.5**):

- EN → EEx e IIC T6
- IEC → Ex e IIC T6

For the following considerations the ignition protection type *Increased Safety "e"* for motors in conjunction with the associated motor protection is of primary interest. It should thereby be noted that the motor protective devices should be installed outside the hazardous areas. This application option is specially identified under CENELEC (see Section **2.4.7.5**). With this ignition protection type, special precautions are taken to ensure an increased margin of safety and to avoid the occurrence of impermissibly high surface temperatures and of sparks or electric arcs inside or outside the electrical equipment.

2.4.7.3 Motors for hazardous areas

Electrical drives that are operated in hazardous areas must be built and engineered so that they cannot become an ignition source. This applies not only to normal operating and starting, but also in case of faults, for example at stalled rotor.

The specified temperature limits for hot surfaces as a potential source of ignition have for ignition protection types *Flameproof enclosures "d"* (transfer of an explosion to the outside excluded) and *Pressurized enclosures "p"* (Ex-atmosphere is kept away from the source of ignition) to be complied with only on the outside of the enclosure. Due to the lag in temperature changes of the motor housing, short-term temperature rise of the windings over the limit temperature of the temperature class are with these ignition protection types regarded as non-critical from an explosion protection viewpoint. In contrast, with a motor of ignition protection type Increased *Safety "e"* (suppression of sparks and high temperatures), exceeding the limit temperature of the corresponding temperature class, for which the motor is foreseen, inside the motor even short-term is not permissible.

		Limit temperatures (°C)					
Temperature class		T1	T2	T3	T4	T5	T6
Ignition class IEC/EN 60079-14, Tab.1	>	450	300	200	135	100	85
Maximum surface temperature EN 50014. Tab.1; IEC/EN 60079-14 Tab.1	≤	450	300	200	135	100	85
Windings class F continuously EEx e, EN 50019, Tab. 3	≤	130	130	130	130	95	80
Winding class F at end of t_E EN 50019, Tab. 3	≤	210	210	195	130	95	80
(white)	= determined by the temperature class of the gas						
(grey)	= determined by the temperature class (isolation class) of the windings						

Tab. 2.4-4
Limit temperatures of electrical machines of ignition protection type "e" with insulation material class F. IEC 60079-14 ed. 4.0. Copyright © IEC, Geneva, Switzerland. www.iec.ch

Based on the requirement that premature damage and ageing of the motor windings must be reliably prevented, there is a further limitation with respect to the heating characteristic of the windings: The permissible ultimate temperature rise corresponding to the insulation material class (temperature class) of the windings is reduced compared to the normal values by 10 to 15 K in motors of ignition protection type "e". In theory this signifies a doubling of the windings life span and serves to increase safety, also resulting however in a reduction of the power output compared with the standard values for a motor of the same size.

The permissible limit temperature of a winding in an electrical machine of ignition protection type *Increased Safety "e"* depends, on the one hand, on the temperature class from the explosion protection viewpoint and, on the other, on the insulation material class of the winding. **Tab. 2.4-4** shows the relevant limit values for motors of isolation class F.

If another insulation material is used, these values change according to the temperature class of the insulation material (**Tab. 2.4-5**).

	Limit temperatures (°C)			
Insulation class	E	B	F	H
„d“, Continuous service	115	120	145	165
„e“, Continuous service	105	110	130	155
„e“, at the end of the t_E-time	175	185	210	235

Tab. 2.4-5
Limit temperatures of motors of ignition protection type “e” and “d” in relation to the insulation material class of the windings

With respect to the temperature rise characteristics of an electrical machine, two operating statuses should be taken into account: continuous duty and stalled rotor motor.

At continuous duty under full load the machine slowly heats up and after several hours, depending on its size, reaches its steady-state temperature. At the highest permissible ambient temperature, this steady-state temperature may not exceed the limit temperature of the insulation material class nor of the temperature class.

In the schematically presented example of the heating characteristics of a machine of insulation material class F in **Fig. 2.4-15**, neither the permitted limit of temperature class T4 nor that of insulation material class F are exceeded once the steady-state temperature has been reached.

The second operating case should be considered as more critical. It occurs if the rotor of the 3-phase asynchronous motor becomes stalled after running at service temperature. The current that then flows is several times higher than the rated current and causes the temperature of the rotor and stator windings to rise rapidly. A monitoring device must disconnect the machine from the supply within the *heating time* t_E, i.e. the time for the limit temperature of the windings to be reached. The *heating time* t_E is the time after which the permissible temperature is reached with a stalled rotor condition starting from service temperature. It is a characteristic quantity of the motor.

As the selected example of a motor with stalled rotor in **Fig. 2.4-15** shows, the limit temperatures of the temperature class for applications T4 and T3 determine the t_E-time.

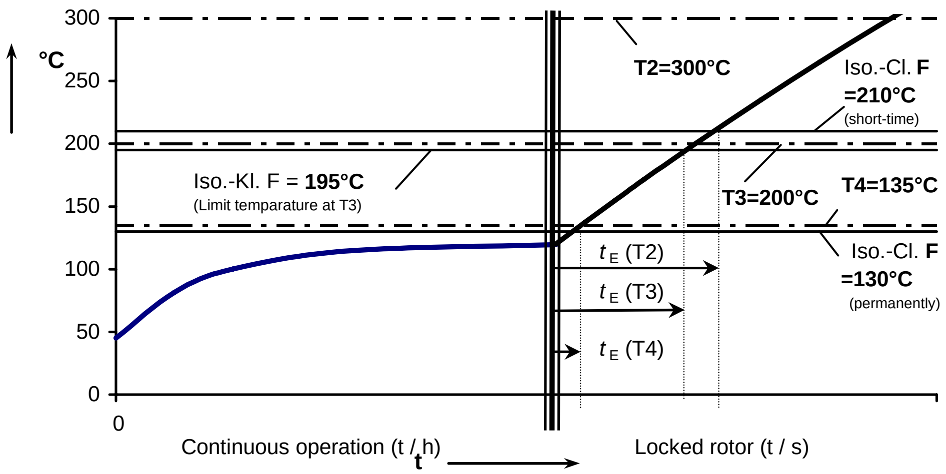


Fig. 2.4-15
Schematic presentation of the heating characteristic of a motor. When locked at service temperature, the motor must be disconnected from the supply within the t_E time.

If however the machine is intended for hazardous areas of temperature class T2 (or T 1), the thermal limit is determined by the short-term permissible limit temperature of isolation material class F of 210 °C.

Ex-motors are not inherently explosion protected. They achieve the required explosion protection by means of complementary installation measures, including appropriate selection of equipment and service conditions. With explosion protection type *Increased Safety "e"* this particularly requires connection to a correctly selected and adjusted overload protective device.

2.4.7.4 Protection of motors of ignition protection type Increased Safety "e"

For the overload protection of motors of ignition protection type Increased *Safety "e"*, the following regulations and standards apply.

- IEC/EN 60947-1, IEC/EN 60947-2 and IEC/EN 60947-4-1 and IEC/EN 60947-8
- IEC/EN 60079-14, Electrical installation in hazardous areas (other than mines), Sections 7 a and 11.2.1

Among others, the following protective equipment can be considered for use:

- Current-sensing overload protective equipment with delayed release
- Equipment for direct temperature monitoring with the aid of temperature sensors

Protection by current sensing motor protective devices with delayed overload release

Overload protection for motors of ignition protection type "e" must be selected so that it monitors the rated current I_N and can switch off a motor with a locked rotor at all poles within the heating time t_E. The heating time t_E is the time after which the permissible temperature of the motor is reached when the rotor is locked at service temperature. The overload protection must release according to its cold curve as in most cases the protective relays cool down already after a short break, while motors take much longer to cool down. The starting (locked-rotor) current I_A and the heating time t_E should be obtained from the rating plate of the motor.

The trip characteristics of the overload protection must always be available at the operating site or via Internet. The release characteristics should indicate the trip times t_A with 3-pole loading, starting from the cold state as a function the starting current ratio I_A/I_N – at least 3 to 8 times. The actual trip times must lie within a tolerance band of ±20 % of the stated values.

The trip times t_A of the overload protective devices must be smaller than the heating time t_E of the motor to be protected for the I_A/I_N ratio given.

When selecting the overload relay, it should be noted that although a short tripping time t_A reliably ensures shutdown within the heating time t_E, the start up of the motor must be possible without any disruption.
IEC 60079-7 and EN 50 019 stipulate minimum values for the t_E time of motors (**Fig. 2.4-16**).

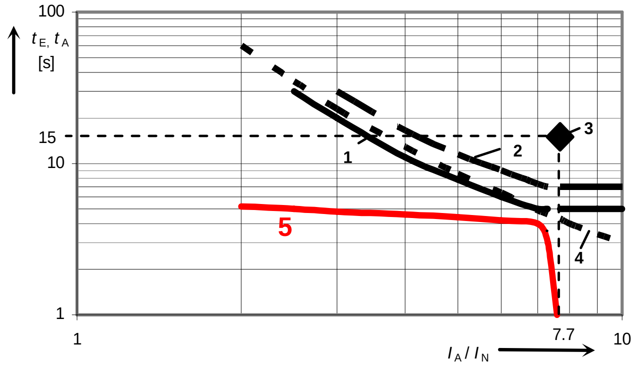


Fig. 2.4-16
Heating time t_E (minimum value) of motors and tripping time t_A of a circuit breaker with motor protection characteristic as a function of the starting current ratio I_A/I_N

1 *Minimum values for the time t_E of motors in accordance with IEC 60079-7 and EN 50019*
2 *Minimum values for the times t_E of motors in accordance with recommendation of the Vereinigung Industrieller Kraftwirtschaft (German "Association of Industrial Power Utilities")*
3 *A motor to be protected with t_E =15 s at I_A/I_N = 7.7*
4 *Trip characteristic $t_A = f(I_A/I_N)$ of a typical circuit breaker with motor protection characteristic of trip class 10*
5 *Starting current of the motor*

Current-measuring overload relays for protection of Ex e – motors must be equipped with a phase failure protection.

Protection by temperature sensors

As an alternative to monitoring the current, the windings temperature can be measured directly. If overload protection is exclusively provided by the installation of temperature sensors, then the motor must be especially examined and certified. It should thereby be documented that the temperature sensors installed in the stator windings trip reliably, even when the rotor is locked, before the rotor reaches the critical temperature according to the ignition class.

Direct temperature monitoring is usually realized with PTC thermistors. See also Sections **4.1.2.3** and **4.2.4.3**.

Heavy-duty starting and high frequency of operation

Ex -motors with heavy-duty starting create additional requirements in hazardous areas. For starting times that would result in tripping of the protective device set to the t_E-time, precautions are required to reliably avoid impermissibly high temperatures under all operating conditions. Thus for example heavy-duty starting from the cold state is permissible as long as it does not exceed 1.7 times t_E-time and is specially monitored.

As the limit temperature of the respective temperature class may not be exceeded even during start-up, especially adapted motors or protective equipment must be selected.

In the case of motors that are frequently switched, there is also a danger that the permissible limit temperatures of the windings will be exceeded. A current-measuring protective device of the motor by itself is not good enough to protect the motor. Additional monitoring of the coils by temperature sensors can be the solution in this case. This is in turn only possible with machines in which the stator is critical. In this case, motors of ignition protection type ”Flameproof enclosures *d”* have an advantage as short-term exceeding of the limiting windings temperature according to the temperature class is not relevant from the viewpoint of explosion protection. The thermal limit in this case is determined entirely by the insulation material class (temperature class).

2.4.7.5 ATEX 100a (Directive 94/9/EC)

For EEx- applications within the EU and the EEA (EU plus Iceland, Liechtenstein and Norway) only devices and protection systems may be circulated that are certified accordingly under EU Directive 94/9/EC (ATEX 100a or ATEX 95). This also applies to Switzerland on the basis of the bilateral treaties with the EU.

Motor protective devices for the overload protection of motors of ignition protection type “e” are subject to these regulations. These include for example circuit breakers and motor protection relays that themselves are installed outside hazardous areas but that are required for the safe operation of the motors with respect to explosion risks, which are installed inside hazardous areas. Strict regulations are in force with respect to the inspection and certification of the devices, their labeling and measures relating to production control and quality assurance at the manufacturer.

In accordance with ATEX 100a, inspection and certification of devices performed by a recognized standards institute (“Notified Body”; for example the “Physikalisch Technische Bundesanstalt Braunschweig PTB”) is required. In addition the “Notified Body” audits the production monitoring and quality assurance systems of the manufacturer. The certification of the manufacturer is subject to periodic renewal.

Device labeling according to ATEX

The protective devices are in accordance with ATEX 100a to be labeled as follows:

- Name and address of the manufacturer
- CE-mark supplemented with the number of the notified testing institution (for example CE **0102** for PTB)
- Type designation
- Serial number, where applicable

- Year of construction (or code for the year of manufacture)
- Mark Ex supplemented with specifications
  - of the equipment group (for example *II* for miscellaneous areas with explosive atmospheres, not in mines)
    - of the equipment category (for example *2* for devices that may be used in zones 1 and 2, supplemented with the letters *G* and/or *D*; G for explosive gas mixtures or D for dusts). For devices that are used for protection of devices in the Ex-area but which themselves are not installed in the Ex-area, the *2* is placed in brackets

    → for example Ex **II 2 G** or Ex **II (2) G,** Code number under ATEX.
- Devices that are directly used in an explosive atmosphere receive an additional code number to reduce the risk of misunderstandings:

  → for example **EEx e IIC T3,** Code under CENELEC**,** *"e"* for Increased Safety, *IIC* for the explosions subgroup "Hydrogen", *T3* stands for a maximum surface temperature of 200 °C.
- Number of the ATEX certificate (e.g. PTB 04 ATEX 3039; a *"U"* at the end of the ATEX number indicates that the device cannot be deployed alone as complete electrical equipment for the Ex-Area – i.e. for example only in conjunction with a motor).
- Relevant standard (for example EN 60079-14 for electrical equipment in hazardous areas with gas)
- The application instructions associated with the device (trip characteristics etc.) must be available (for example via Internet). The place of availability of information must be stated on the device.

2.4.7.6 IECEx and other approval schemes for hazardous areas

Much of the information in this section refers to ATEX standards. ATEX is a European-based approval scheme, but may not be accepted in some other parts of the world. Other common hazardous area standards include IECEx (mandatory in some countries, such as Australia) and NEC (USA).

Readers should refer to their local national standards for clarification. For IECEx see also www.iecex.com.

3 Starting and switching motors

3.1 Selection criteria

Electrical motors must be accelerated from rest up to the operating speed with a starting device. In the case of variable speed drives, the motor controller must also manage the motor speed during operation. The motor and method of starting selected depend on the load torque, the desired starting characteristic (starting current, acceleration) and on the characteristic of the supply. See also Section **1.7** with respect to the characteristic properties of induction motors as the most frequently used motors.

Main criteria for the selection of the starting method

When making the decision whether to use a

- direct-on-line starter
- electromechanical starter for the starting with reduced current or
- electronic motor control devices (soft starters, inverters)

the following items should be taken into account to find a suitable solution from the points of view of application and productivity:

- How high is the torque required to start the load?
- Can transmission components such as belts, gearboxes or chains be damaged by the high starting torque with direct starting?
- Does the plant require gentle and continuous acceleration or are torque peaks permissible?
- Are there any restrictions with respect to supply loading?
- Do technologically more complex products offer additional functions for optimization of the application (for example pre-warning functions of motor protection relays, mirror contacts for safety controllers, communication links etc.)?
- In addition to starting, are features of controlled coasting to a stop or braking to be taken into account?
- In addition to starting, are aspects of speed control to be taken into account once the motor has started (for example from process engineering or energy saving perspectives)?

The selection of suitable starting methods is a critical factor in achieving optimum economic efficiency in every motor control application. **Tab. 3.1-1** provides guidance with respect to the various methods for starting squirrel-cage induction motors.

Kind of motor	Starting procedures for squirrel-cage standard motors compared (typical values)								Special squirrel-cage motors	
Method of starting	Direct on Line (DOL)	**Y–Δ-** normal	**Y–Δ-**closed transition	Auto-transformer	Start via chokes	Start via resistors	Soft starters	Frequency inverters	**Y–Δ-** enhanced starting torque	Multi-stage start
Mains	strong	weak	weak	weak-medium	medium	medium	weak-medium	weak	medium	medium-strong
Load during start	full	low	low	low-medium	low-medium	low	low-medium	low-medium	medium	medium-full
Relative starting current I_A/I_e [1]	4 ... 8 (= I_{AD})	1.3 ... 2.7 (= 1/3 I_{AD})	1.3 ... 2.7 (= 1/3 I_{AD})	1 ... 5 (=0.25…0.65 I_{AD}) selectable	2 ... 4	2 ... 4	2 ... 6	1 ... 2	2 ...4	2 ... 8
Relative starting torque T_A/T_e [3]	1.5 ... 3 (= T_{AD})	0.5 ... 1 (= 1/3 T_{AD})	0.5 ... 1 (= 1/3 T_{AD})	0.4 ... 2 (=0.25…0.65 T_{AD})	0.4 ... 0.8	0.4 ... 0.8	0.15 … 2 $T_A = k^2 \cdot T_{AD}$ [3]	T_A adjustable [4]	0.7 ... 1.5	0.7 ... 3
Run-up time (normal)	0.2 ... 5 s	2 ... 15 s	2 ... 15 s	2 ... 20 s	2 ... 20 s	2 ... 20 s	0.5 ... 10 s	0.5 ... 10 s	2 ...10 s	0.2 ... 10 s
Run-up time (heavy duty start)	5 ... 30 s	15 ... 60 s	15 ... 60 s	20 ... 60 s	unusual for loaded start		10 ... 60 s	5 ... 60 s	10 ... 40 s	5 ... 30 s
Characteristic features	High acceleration with high starting current	Start with reduced torque an current; current and torque peaks at switchover	Like normal Y-Δ, considerably reduced peaks at switchover	Similar to Y–Δ, but without switchover-interruption; selectable steps	Voltage and motor current (and thus relative torque) increases with speed	Voltage and torque increase less with speed compared to chokes	Adjustable starting characteris-tics. Also controlled Stop possible.	High available torque at low current. Adjustable starting characteristics.	Like normal Y–Δ, but at higher levels of current and torque.	Starting currents and torques depending on motor design.
Application area	Drives in areas with strong power supply which permit the high starting torque	Drives which are only loaded after run-up	Like normal Y–Δ, but for loads with little inertia mass and high resistance torque.	Predominantly English speaking countries Like Y–Δ-starters.	Drives with resistance torque increasing with speed.	Cost-effective for unloaded starts. With resistance steps more expensive and more flexible.	Starts which require a gentle or adjustable torque characteris-tic (or reduced starting currents).	Usually for operational speed adjustment. Energy saving possible.	Drives with high available torque at start-up..	Usually for operational speed adjustment.

[1] I_A = Motor starting current, I_e = Rated operational current of Motor [2] T_A= Motor-Starting torque T_e =Rated operational torque of Motor
[3] k = Voltage reduction factor T_{AD} =Motor starting torque at full voltage [4] Start frequency controlled, torque wide range adjustable

Tab. 3.1-1
Characteristic features of the commonly used starting methods for squirrel-cage induction motors

3.2 *Direct starting of squirrel-cage induction motors*

The direct starting (Direct On Line, DOL) is the simplest and most cost-efficient method of starting a motor. This is assuming that the power supply can easily deliver the high starting current and that the power transmission components and the working machine are suitable for the high starting torques.

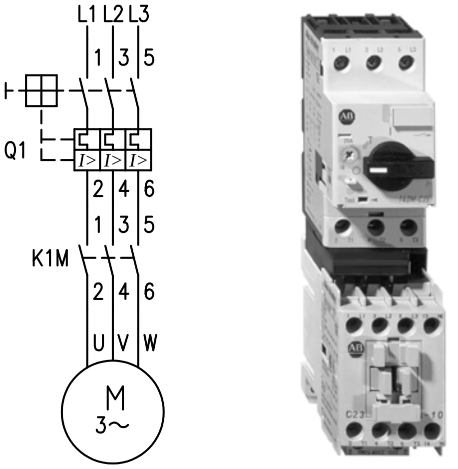


Fig. 3.2-1
Example of a two-component starter for direct starting consisting of a motor protection circuit breaker and a contactor

With direct starting, the poles of contactor and motor protective device are connected to the pole conductors (**Fig. 3.2-1**) and the operating current of the motor flows through them. The motor protective device must therefore be adjusted to the rated operational current of the motor.

The contactor is selected according to the rated operational current I_e and the respective utilization category:

- AC-3 Squirrel-cage induction motors: Starting, switching off during running
- AC-4 Squirrel-cage induction motors: Starting, plugging, inching

Definition of utilization categories see Section **1.1**.

For AC-3 operation, allowance must always be made in practice for sporadic inching operations, for example during commissioning, in case of faults or in service work. Contactors from Rockwell Automation comply with these requirements and may be rated without risk according to AC-3 values; for the large majority of devices, the rated operational currents for the utilization categories AC-3 and AC-4 are the same.

A considerable proportion of AC-4 operations or exclusive AC-4 operation is in practice relatively rare. In such cases, a high frequency of operation is often required at the same time and a high electrical life span is expected. Thus the contactor must be selected according to these two criteria. In most cases a larger contactor must be used than would correspond to the maximum permissible AC-4 rated operational current. See also Sections **2.3.6.3** and **2.3.7**.

3.2.1 Starting time

The starting time is an important parameter in starter engineering, as the starting current can be many times higher than the rated currents of motor and switchgear and correspondingly places the latter under thermal loading. It depends on the torque of the motor and hence on the selected starting method, as well as on the torque characteristic of the load. The difference between the motor torque and load torque is the acceleration torque. In addition to the resistive torque of the drive, the inertial mass to be accelerated has a key influence on the time taken for motor starting.

The duration of so called no-load starting, i.e. starts without loading of the drive, typically lies, depending on motor size, in the time range of under 0.1 to around 1 s, starting under load (but without large flywheel masses) up to around 5 s. For centrifuges, ball mills, calenders, transport conveyors and large fans, the start times can extend to minutes. In the case of pumps and fans it should be noted that the pumped material (liquid, air) contributes to the effective inertial mass. The above given approximate values apply for direct starting. The times are correspondingly extended with starter methods with reduced starting current and torque.

With respect to the permissible starting time of the respective motor, the manufacturer's documentation is definitive.

For the selection of contactors for heavy-duty starting, see Section **2.3.5.2**.

3.2.2 Reversing starters

In a reversing starter the motor is switched via two contactors, one for each direction. If the motor is started from rest, the contactor is selected according to utilization category AC-3. Often however the motor direction is changed while it is running (plugging), which means a correspondingly higher loading of the contactors and hence requires selection according to utilization category AC-4. Direct reversing requires a reversing delay between the contactors – for example by means of a short-term delay – of around 40 ms, to prevent short-circuits between phases. In addition to electrical interlocking of contactors of reversing starters, mechanical interlocking is recommended.

Corresponding precautions as for reversing starters are required for plugging with stopping at standstill. In this case when the motor comes to rest, the braking contactor (for example controlled by a speed sensor) is switched off and the motor is hence disconnected from the supply.

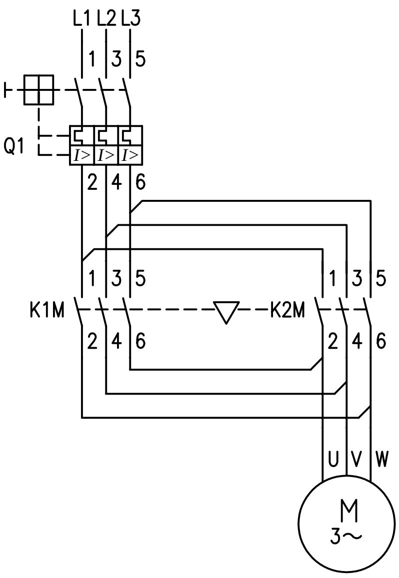


Fig. 3.2-2
Reversing starter with motor protection-circuit breakers and mechanical interlock: Diagram and layout

3.3 Star-delta (Y-Δ, wye-delta) starting

Star-delta (in North America the designation "wye-delta" is commonly used instead) starting is the simplest method for reducing the starting current of a motor. The technique can be used with all squirrel-cage induction motors that are delta-connected for normal operation and whose windings ends are individually connected to terminals. The reduction of the motor current causes a reduction of the starting torque. Star-delta starting is therefore especially suitable for drives that are not loaded until after starting. The starting time is longer than with direct starting, which is especially apparent when driving larger inertial masses.

A distinction should be made between

- normal star-delta starting
- star-delta starting with closed transition
- amplified star-delta starting.

3.3.1 Normal star-delta starting

Circuit connections and switching-over procedure

On initiation of starting, the supply voltage is applied to the star-connected motor windings. The starting torque and the starting current in this circuit are approx. 30 % of the values for delta connection. Because of the reduced torque in star connection, the motor does not quite reach the rated speed. After star-connected start-up, the windings are switched-over to delta connection.

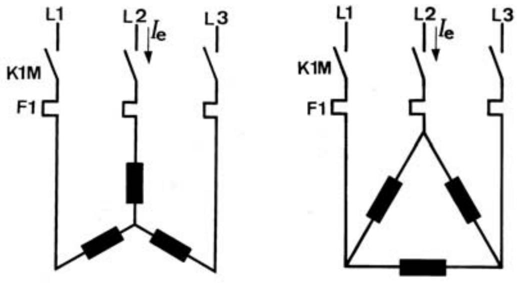


Fig. 3.3-1
When starting in star connection, the phase voltage is applied to the motor windings and a windings current of $I_{WY} = I_{W\Delta}/\sqrt{3}$ flows.
Because of vectorial addition of the windings currents in delta connection $I_{eY} = I_{e\Delta}/3$.

On switching from star to delta operation, there is a current surge, whose magnitude depends on various factors. In the figures below, typical cases are illustrated.

Fig. 3.3-2 shows the ideal case for such a switchover. The motor nearly reaches its rated speed in the first stage, as the load torque during starting is relatively low. The switching-over current surge is around the same size as the starting current.

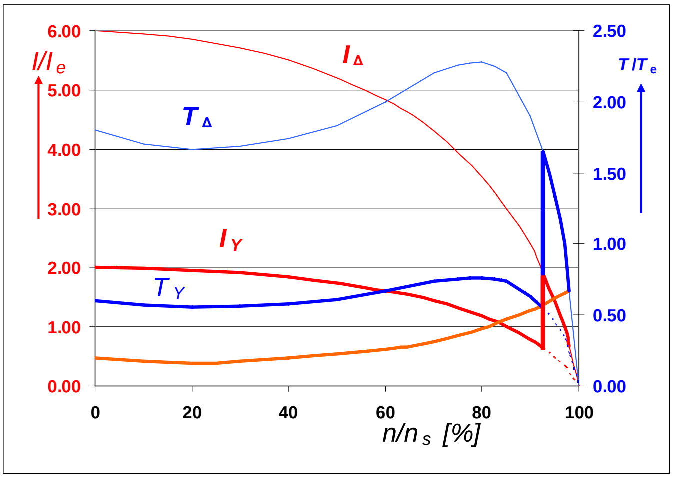


Fig. 3.3-2
Typical characteristic of current and torque for star-delta starting

I	=	*motor current*
I_e	=	*rated operational current of the motor*
I_Y	=	*current in star connection*
I_Δ	=	*current in delta connection*
I_A	=	*current characteristic with star-delta starting*
T	=	*torque*
T_e	=	*rated operational torque of the motor*
T_Y	=	*torque in star connection*
T_Δ	=	*torque in delta connection*
T_L	=	*load torque*
n	=	*speed*
n_s	=	*synchronous speed*

Switching-over itself is usually automatic (rarely manual) and performed by a timing relay set to the required operating period of the star contactor. Between switching off of the star contactor and the making of the delta contactor there must be a sufficient time interval to be certain that the breaking arc in the star contactor is quenched before the delta contactor is switched on. If switching-over is too rapid, the breaking arc causes a short-circuit and the short-circuit protection disconnects the circuit (see **Fig. 3.3-3**).

On the other hand, when the switching interval is too long, the motor speed falls during the de-energized interval, depending on inertial mass and load, so strongly that the in-rush current in the delta connection is very high, defeating the purpose of the star-delta start up (**Fig. 3.3-4**).

A sufficiently long switching interval between breaking of the star contactor and making of the delta contactor is achieved in small contactors with short pull-in and dropout times by electronic timing relays with a switching-over delay of approx. 50 ms. Larger contactors have an inherent switching delay of > 25 ms. In this case, timing relays without additional switching delay may be used. The switching interval then is of the optimum length. To avoid phase short-circuits, the star and delta contactors are additionally mechanically interlocked.

If the delta contactor is switched via an auxiliary contactor (e.g. at low control voltages), no switching-over delay is required on the time relay. A switching interval of adequate length results from the sum of the making delay times of the auxiliary and delta contactor.

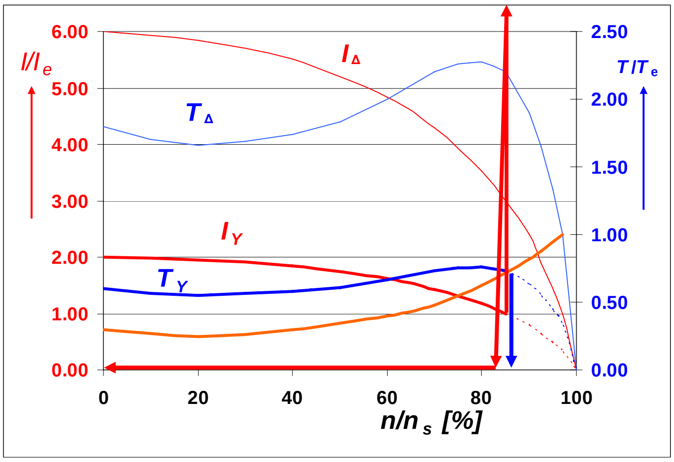


Fig. 3.3-3
A switching interval that is too short results in a short-circuit via the switching arc – the short-circuit protection is activated and breaks the circuit

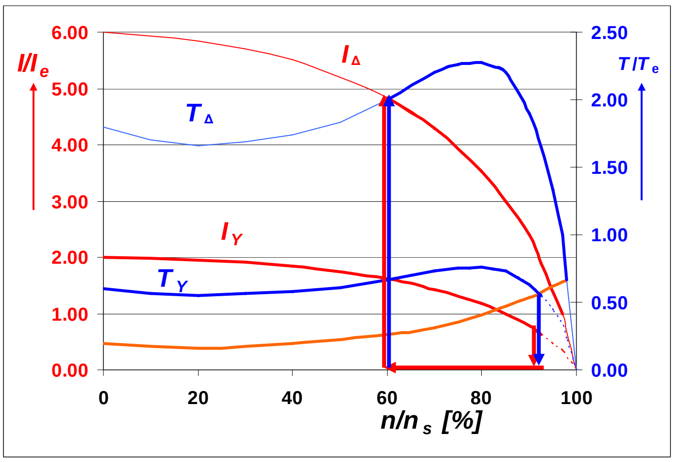


Fig. 3.3-4
With switching intervals that are too long, the speed falls again behind → direct starting in delta connection

Faults like shown in **Fig. 3.3-3** and **Fig. 3.3-4** can also be avoided with the interruption-free (closed transition) star-delta circuit (Section **3.3.4**).

When the load torque is too high the star-connected motor only accelerates to a fraction of the speed and "sticks" at this speed. The switching process would proceed as in **Fig. 3.3-5** and the purpose of the star-delta start up would not be achieved.

Moreover this condition means that the contactors have to switch off a multiple of the motor rated current. In the example in **Fig. 3.3-5** the breaking current is around 1.3 · I_{emotor}. The star contactor is selected according to $I_{e(Y\ contactor)} = 0.34 \cdot I_{emotor}$ (see below) and must accordingly switch off

$$1.3/0.34 \approx 4 \cdot I_{e(Y\ contactor)}$$

In practice this means AC-4 operation with a correspondingly reduced electrical life span. In this case a motor for amplified star-delta starting (Section **3.3.5**) should be used.

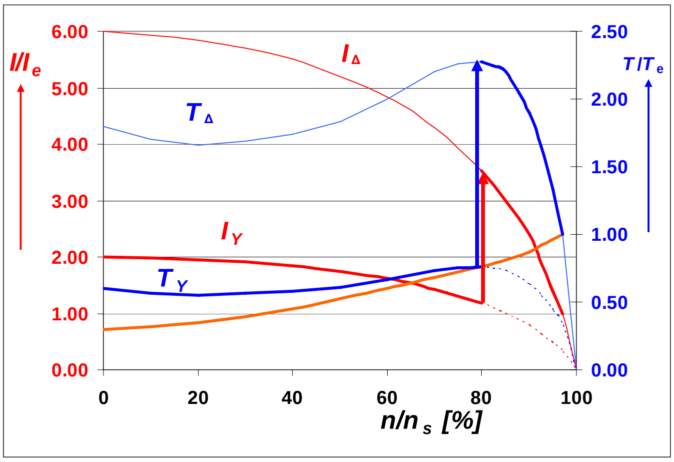
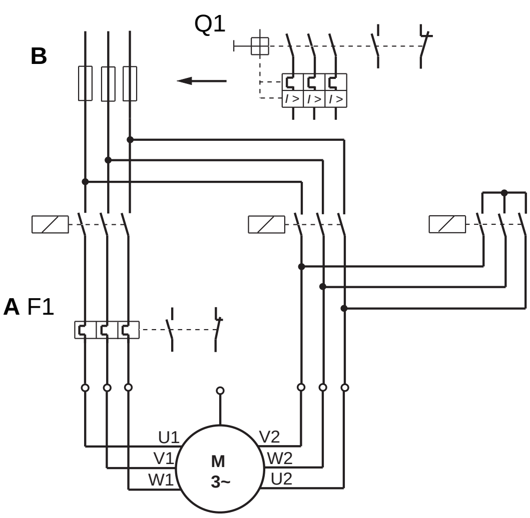


Fig. 3.3-5
Switching-over at speed- that is too low

Selecting the starter components

With star-delta circuits in accordance with **Fig. 3.3-6** in delta mode the circuits of main contactor, delta contactor and motor protection relays are connected in series to the motor windings (**Fig. 3.3-7**). The devices are therefore loaded with the phase current I_p:

$$I_p = I_e/\sqrt{3} = 0.58 \cdot I_e$$



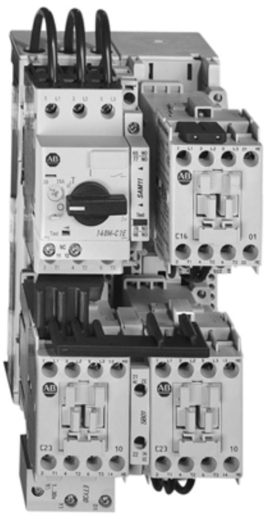


Fig. 3.3-6
Starter for normal star-delta starting

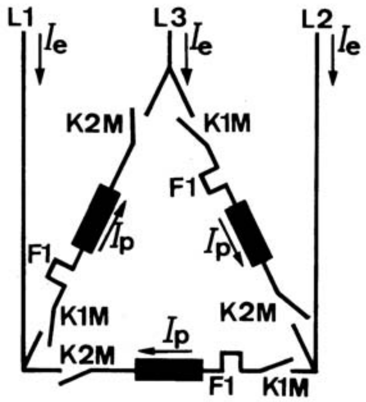


Fig. 3.3-7
Contactor contacts and motor protection relays are connected in series to the motor windings in delta connection
K1M Main contactor
K2M Delta contactor
F1 Thermal relay
I_e Rated operational current of the motor
I_p Phase current

For normal star-delta starting, the switchgear should be rated for the following rated operational currents:

Main contactor	K1M = 0.58 · I_e	
Delta contactor	K2M = 0.58 · I_e	
Star contactor	K3M = 0.34 · I_e	
Thermal relay	F1 = 0.58 · I_e →	Motor protection in Y- and Δ- operation, with F1 in Pos. **A** (**Fig. 3.3-6**), $t_A \leq 15$ s (normal starting)
Circuit breakers	Q1 = 1.00 · I_e →	Restricted motor protection in Y- operation, with Q1 in Pos. **B** (**Fig. 3.3-6**), $t_A > 15 \ldots 40$ s

The selection of contactors according to these values applies for starting times of maximum 15 seconds and 12 starts per hour. With heavy-duty starting or higher frequencies of operation, a larger contactor K3M, possibly also K1M, should be selected (see Sections **2.3.5.2** and **2.3.6**).

Equally the electrical life span of contactors, especially of the star contactor, should be reviewed (see Section **2.3.6.3**). If e.g. switching-over occurs at too low a speed, the star contactor has to break many times its rated current (**Fig. 3.3-5**). This would strongly reduce its electrical life span.

3.3.2 Motor connection for clockwise and counterclockwise direction of rotation

When the delta contactor connects at adverse vectorial positions of the supply voltage and the rotor field, transient processes could occur in the motor that could lead to larger current peaks than at switching-on the delta-connected motor . This can result in the making capacity of the contactors being exceeded with as a consequence welding of contacts.

The transient currents can be reduced by appropriate wiring of the main circuit (**Fig. 3.3-8**). Besides the load on the contactors, this also reduces the dynamic stress on the windings-heads in the motor.

Lower transient currents peaks with correct wiring (clockwise rotation)

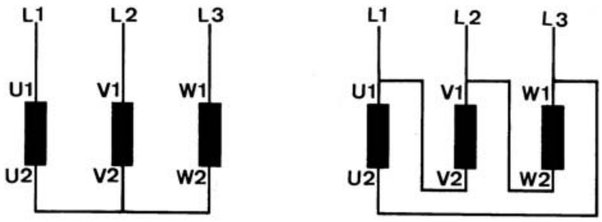


Fig. 3.3-8
Correct connection of motor phases for clockwise rotation

During the de-energized switching interval, the rotor falls back against the rotating field of the power supply. Its magnetic field induces a decaying residual voltage in the stator – in the voltage phasor diagram **Fig. 3.3-9** for the pole conductor L1 entered as $U_{L1'\text{-}N}$.

When connecting to delta (**Fig. 3.3-8** und **Fig. 3.3-9**) the mains voltage $U_{L1\text{-}L3}$ is applied to the stator winding, across which this residual voltage is still present. The differential voltage ΔU is relatively small, thanks to the favorable vectorial position of the residual voltage $U_{L1'\text{-}N}$ and the supply voltage $U_{L1\text{-}L3}$ that are approximately oriented in the same direction. Thus the current surge generated by this resultant voltage will also remain small.

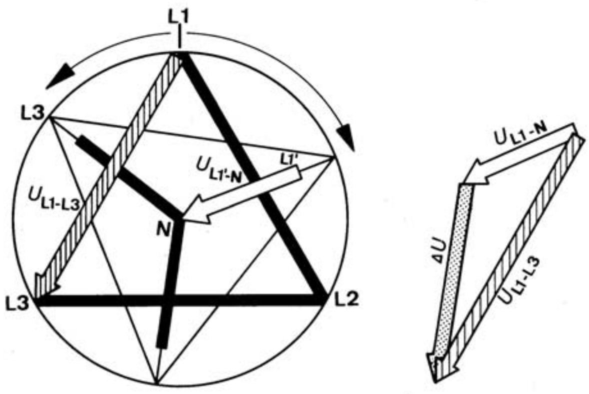


Fig. 3.3-9
Phasor diagram for star-delta with correctly connected motor phases for clockwise rotation

High transient current surge with incorrect wiring

The motor also turns clockwise when the terminals are connected according to **Fig. 3.3-10**.

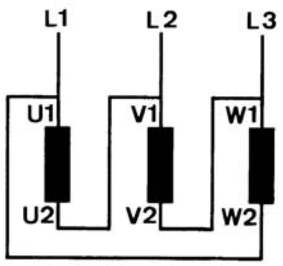


Fig. 3.3-10
Incorrect connection of the motor phases also produces clockwise turning

A decaying residual voltage acts again with lagging phase position in the stator during the switching interval. On switching to delta, the phase winding with the phasor $U_{L1'\text{-}N}$ is connected to the supply phase $U_{L1\text{-}L2}$. These two voltages however have totally different vectorial directions, the differential voltage ΔU is high and results in a correspondingly high transient current surge.

Switching from star to delta produces the phasor diagram **Fig. 3.3-11**

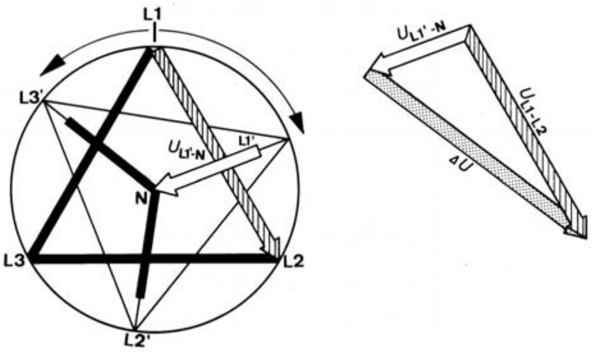


Fig. 3.3-11
Phasor diagram for connections of the motor phases according to Fig. 3.3-10. This produces a high transient current surge because of the adverse vector position.

Counterclockwise sense of rotation

To run the motor in the counterclockwise direction, it is not enough to swap around two phases at any point. This would produce the same relationships as described above. In order to keep the transient current surge from star to delta connection as small as possible the wiring must be arranged as in **Fig. 3.3-12**.

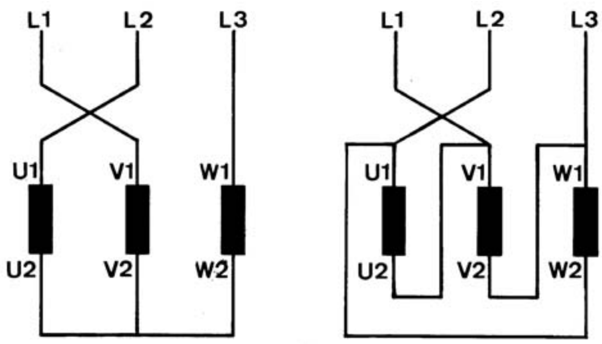


Fig. 3.3-12
Correct connection of the motor phases for counterclockwise rotation of motor

3.3.3 Influence of the third harmonic on motor protection relays

In motors, in which there is relatively little core iron (e.g. refrigeration motors, submersible pump motors etc.), with delta connection the third harmonic and its harmonics are excited in the windings as a consequence of iron saturation. Because of the triple frequency the currents of the third harmonic have the same vector position in all three windings. This harmonic current basically flows in a circle through the windings and is not noticeable in the feeding lines. With star connection, no third harmonics can form as the motor star point is not connected to the mains.

Experience shows that the harmonic current values can be up to 30 % and more of the basic current. With measuring instruments that show the true r.m.s. value, the r.m.s. value of the entire windings current can be measured; on the other hand, the harmonic component cannot be correctly measured by instruments that only show the mean value.

The third harmonic contributes to heating of the motor windings. This is taken into account by the motor manufacturer so that the rated load is not compromised. Therefore motor protective devices for direct starting in delta mode should always be set to the motor rated operational current (= current in feeding lines).

In delta mode in a star-delta starter the motor protective device is connected in series to the motor windings (**Fig. 3.3-7**). If it is normally set to 0.58 · I_e it may release prematurely due to the additional harmonics. In these cases the actual r.m.s value of the windings current should be measured and the setting of the protective device should be increased by the percentage of the harmonic current. This applies for motor protective devices such as bimetal relays, whose trip characteristic is based on the r.m.s. value of the current.

Electronic motor protective devices frequently use measuring principles that differ from the above (for example based on the peak value of the current). In these cases, the settings adjustment must be made on the basis of practical tests.

3.3.4 Uninterrupted star-delta starting (closed transition)

With this circuit (**Fig. 3.3-14** and **Fig. 3.3-15**) the decay of the motor speed during star-delta switching is avoided and the subsequent current peak is kept small.

Before the star contactor is opened, a fourth (transition) contactor K4M makes the motor circuit via resistances in delta. This means that the motor current is not interrupted during switching-over (**Fig. 3.3-13**) and the motor speed hardly falls. The delta contactor K2M then establishes the final state of operation and drops out the transition contactor K4M.

As the normal star-delta circuit, this circuit is only suitable for starting with small load torques.

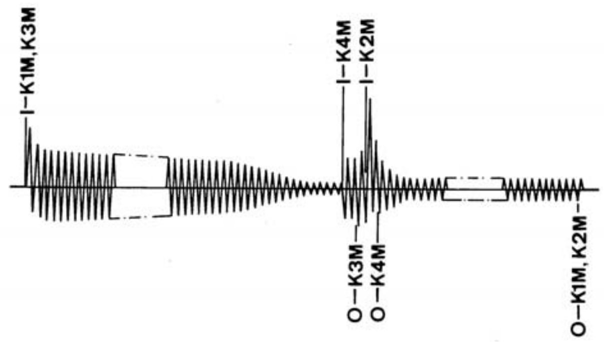


Fig. 3.3-13
Oscillogram of star-delta starting with closed transition

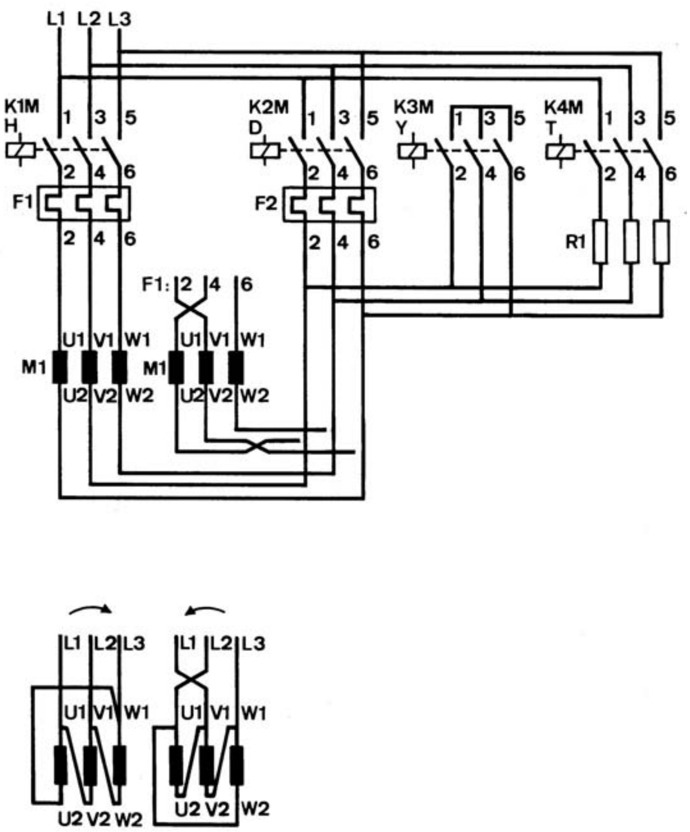


Fig. 3.3-14
Star-delta starter for closed transition

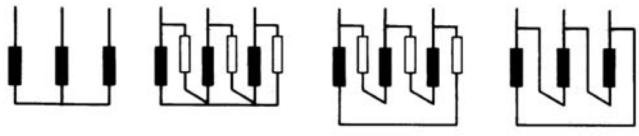


Fig. 3.3-15
The four switching steps of the closed transition star-delta – circuit
A Starting in star – connection
B Switching-over: Star and transition contactors are closed
C Switching-over: Delta circuit via transition contactor and resistors
D Operation in normal delta circuit

Rating of starters

Main contactor	K1M	$0.58 \cdot I_e$
Delta contactor	K2M	$0.58 \cdot I_e$
Star contactor	K3M	$0.58 \cdot I_e$
Transition contactor	K4M	$0.27 \cdot I_e$ (typical value, varies with R1)
Overload relay	F1	$0.58 \cdot I_e$
Transition resistor	R1	$(0.35...0.4) \cdot U_e/I_e$ The factor should be selected from the stated range so that a standard resistance value results.

Unlike in the normal star-delta circuit, the star contactor in the starter for closed transition has the same rating as the main and delta contactor. This is for two reasons:

- The K3M star contactor must break the star current of the motor and of the transition resistances. A current of approx. $1.5 \cdot I_e$ flows in the transition resistors. Therefore a correspondingly higher contact rating is required.

- The closed transition star-delta circuit is often used in plants with higher frequencies of operation, in which also a longer electrical life span is required.

The resistors are only loaded for a maximum of 0.1 seconds (short-time duty). However in most cases only the continuous load capacity of the resistors is known. For wired ceramic-tube resistors the continuous load capacity P_R required for selection can be calculated by help of the following approximation formulas:

$P_R \approx U_e^2/(1200 \cdot R)$ [W] for max. 12 operations/h

$P_R \approx U_e^2/(500 \cdot R)$ [W] for max. 30 operations/h

Notes

In a star-delta circuit with closed transition, no excessive switching current surge can be produced. With large inertial masses, it should also be ensured that the motor is correctly wired for clockwise or counterclockwise rotation (see Section **3.3.2**), to prevent damage by torque surges.

3.3.5 Amplified star-delta starting

With a large load torque, an adequate speed is not achieved in the normal star connection because of the reduction of the starting torque of the motor (see **Fig. 3.3-5**). A larger motor torque can be achieved with amplified star-delta starting. That being said, the starting current also increases with the motor torque (see **Tab. 3.1-1**).

Two starting methods are possible:

- Mixed star-delta starting
- Part winding star-delta starting

For both methods, motors with suitable windings tappings are required.

Mixed star-delta starting

In this case the motor windings are usually divided into two equal halves. On starting, one half of the part-windings is delta-connected, the other is star-connected (**Fig. 3.3-16**). The starting current in star-connection is approx. (2 ... 4) · I_e. This generates a correspondingly larger starting torque.

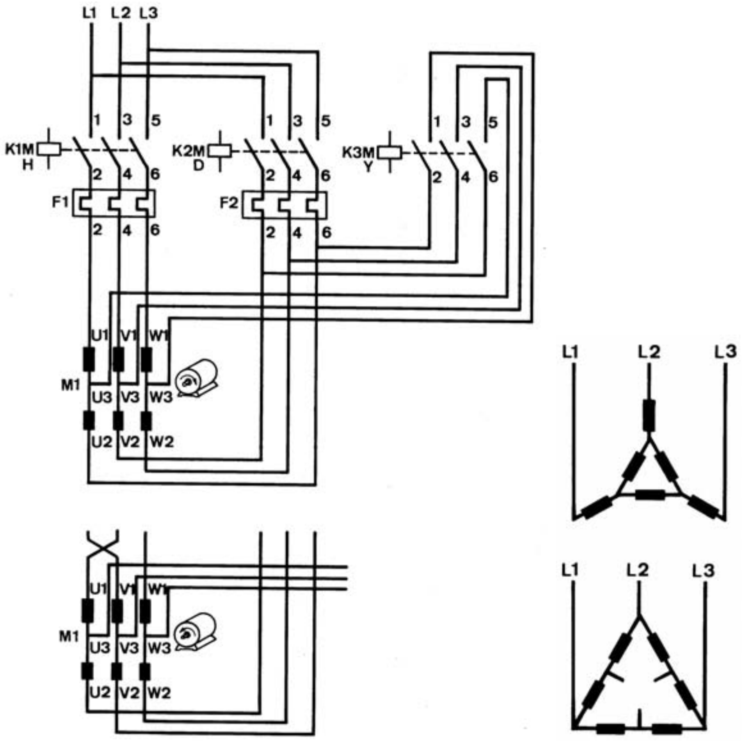


Fig. 3.3-16
Mixed star-delta starting
Circuit diagram and connections of motor coils during starting (Y) and in operation (∆)

3.3.6 Part-winding star-delta starting

In this case, too, the motor windings are subdivided. In the star connection, only the main winding – one part of the entire winding – is used (**Fig. 3.3-17**). The starting current in star connection is (2 ... 4) · I_e, depending on tapping, from which a larger breakaway torque results.

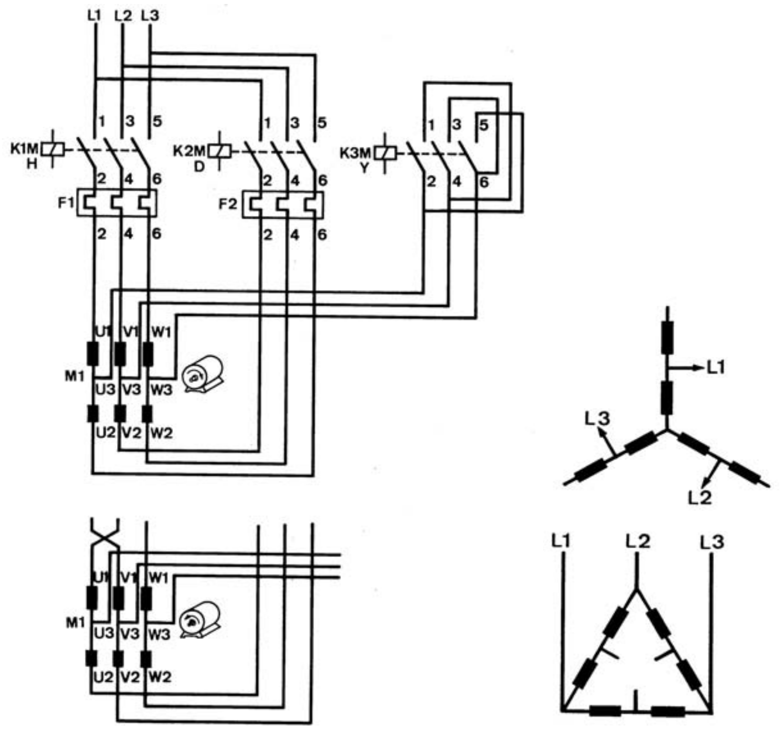


Fig. 3.3-17
Part-winding star-delta starting
Circuit diagram and connections of the motor windings during starting (Y) and in operation (Δ)

Ratings of the starter components

With the exception of the star contactor, contactors and motor protective devices have the same ratings as with the “normal” star-delta circuit (see Section **3.3.1**). The star contactor should be selected for (0.5 ... 0.58) · I_e because of the larger starting current.

Notes

A sufficiently long switching interval for transition from star to delta operation should be ensured, in accordance with Section **3.3.1**. A closed transition star-delta connection in accordance with Section **3.3.4** is possible in both cases. With very large load-torques it may even be necessary. The transition resistor and the transition contactor should be rated as described there.

The rules in accordance with Section **3.3.2** apply for the connections.

3.4 Auto-transformer starting

3.4.1 Circuit and function

An auto-transformer starter makes it possible to start squirrel-cage induction motors with reduced starting current, as the voltage across the motor is reduced during starting. In contrast to the star-delta connection, only three motor leads and terminals are required.
On starting, the motor is connected to the tappings of the auto transformer; transformer contactor K2M and star contactor K1M are closed. The motor starts at the voltage reduced by the transformer, with a correspondingly smaller current.

By this means the feeding current in comparison to direct starting would be reduced by the square of the transformer voltage ratio; nevertheless, it is in most cases noticeably higher, as it also covers the relatively high transformer losses. Depending on the tapping and starting current ratio of the motor, the starting current lies at (1 … 5) · I_e. In contrast, the motor torque falls with the square of the voltage across the windings. Auto-transformers usually have three available taps in each phase (for example 80 %, 65 %, 50 %), so that the motor starting characteristic can be adjusted to the load conditions.

If the motor has reached 80 ... 95 % of its rated speed (depending on the desired reduction of the current surge after switching-over), the star contactor K1M on the transformer is opened. Now the transformer part-windings act as chokes. The motor voltage is only reduced by the chokes below the supply voltage and the motor speed does not fall. The main contactor K3M closes via auxiliary contacts of the star contactor and applies the full supply voltage to the motor. For its part, the main contactor K3M drops out the transformer contactor K2M. The entire procedure is thus uninterrupted.

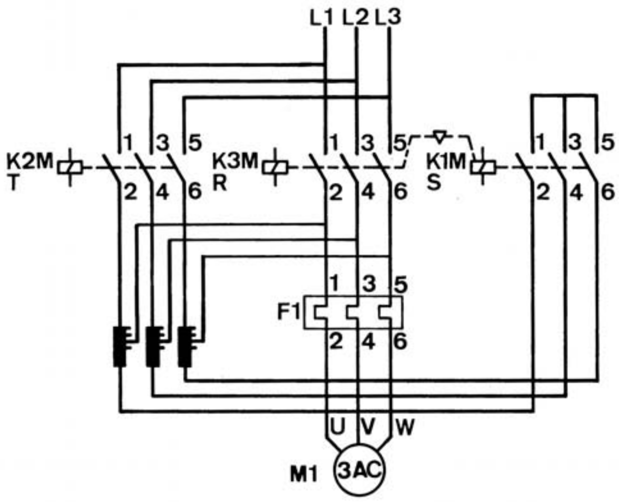


Fig. 3.4-1
Auto-transformer starter with uninterrupted switching over (Korndörfer starting method)

3.4.2 Rating of the starter

The main contactor K3M and the motor protective device F1 are selected according to the motor rated operational current I_e. Transformer contactor and star contactor are only briefly closed during starting. Their rating is determined by the required contact breaking capacity, as they must reliably cope with any unforeseen disconnection during start up. The star contactor also operates with every start-up during switching-over. The values of the rated operational currents for the transformer contactor K2M, depending on the start time and starting current, are between (0.3 … 1) · I_e, for the star contactor between (0.45 … 0.55) · I_e.

3.5 Starting via chokes or resistors

The series-connected chokes (**Fig. 3.5-1**) or resistors (**Fig. 3.5-2**) reduce the voltage at the motor and hence also the starting current. The starting torque is reduced by around the square of the current.

3.5.1 Starting via chokes

At rest the motor impedance is small. Most of the supply voltage drops across the series-connected chokes. The breakaway torque of the motor is therefore strongly reduced. With increasing speed, the voltage across the motor increases because of the fall of the current consumption and the vectorial voltage distribution between the motor and the reactance connected in series. Hence the motor torque also increases. After the motor start-up, the chokes are shorted by the time-delayed main contactor K1M and the starting contactor K2M is dropped out.

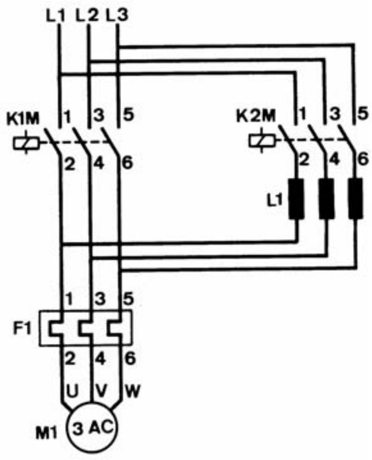


Fig. 3.5-1
Motor starting via series-connected chokes

3.5.2 Starting via resistors

The basic circuit diagram is the same as described in Section **3.5.1**, only that the chokes are replaced by lower-cost resistors.

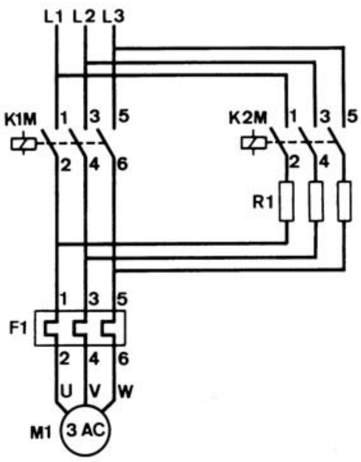


Fig. 3.5-2
Motor starting via series-connected resistors

With this method, the starting current can only be slightly reduced, as the motor torque falls with the square of the voltage and the voltage across the motor, other than with starting via chokes, only increases slightly with increasing speed. It is more advantageous to reduce the series-resistance during starting in steps. This reduces the voltage across the resistor and increases that across the motor. The expenditure on hardware is thereby significantly larger.

A simpler solution are enclosed electrolytic resistors with a negative temperature coefficient. Their ohmic resistance decreases automatically during starting because of heating by the starting current.

3.6 Stator resistance soft starting

3.6.1 Circuit and function

This method is used with relatively small induction motors with squirrel-cage rotors to achieve a soft starting effect. The starting torque is reduced because an ohmic resistance is connected in the supply line of one phase (**Fig. 3.6-1**). This means that the motor is asymmetrically supplied, resulting in a more gentle, surge-free motor start-up. The motor current is not reduced in the two phases without series resistance. Modern solutions make use of controlled power semiconductors instead of resistors.

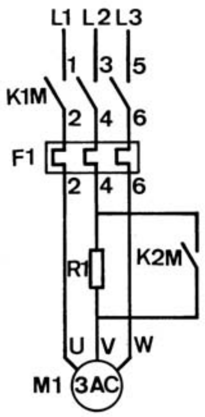


Fig. 3.6-1
Stator resistance soft starting for gentle motor starting

Note
A motor protective device without differential release must be used, as it would otherwise operate during start-up.

3.7 Pole-changing motors

3.7.1 Speed change by pole changing

The number of poles determines the rated speed in asynchronous motors at a given supply frequency. If the stator windings are designed for two or more different pole numbers, the speed can be changed in just as many steps by switching-over.

The Dahlander circuit that with only one winding and six terminals supports two pole numbers and hence speeds in the ratio 1:2 is especially economical. The rated powers and torques of the two steps are thereby in a certain relationship to each other, depending on the circuit version. The Dahlander winding is divided into individual windings groups, stepped according to the smaller pole pitch. When current flows through each windings group in the same direction, the higher pole number is generated, and when the current direction is reversed in each second windings group, the lower pole number is generated. By repetition of the same windings arrangement from pole to pole, a very good windings symmetry is achieved.

A special type of Dahlander circuit is the PAM circuit (pole amplitude modulation). In PAM motors, an asymmetry of the field harmonics is accepted and the windings are grouped so that the resulting pole numbers are in ratios other than 1:2 (e.g. 6/4-pole or 8/6-pole).

Motors in PAM circuits, like those in Dahlander circuits, only have six terminals. For both winding types, the same versions of the external circuit diagram can be used. An additional star point contactor is always required for the YY stage, in addition to the two feeding contactors of both steps.

Pole changing can also be achieved by regrouping the windings branches. This is known as phase mixing or phase modulation. In this case the winding along the periphery is divided into coil blocks. Depending on the number of these blocks, double or multi-stage pole changing can be performed. Three terminals are required per speed level.

With pole changing by phase modulation, the connection diagram provided by the motor manufacturer should be consulted when selecting the external circuit layout and the switchgear. Either only one feeding contactor (for example YYY/YYY circuit) is required per stage or in addition a supplementary bypass contactor (for example $\Delta/\Delta\Delta$ circuit).

In **Tab. 3.7-1** and **Tab. 3.7-2** a summary is provided of the most common arrangements and circuit layouts of stator windings for pole-changing motors.

Number of speeds	Number and type of windings	Common number of poles	Synchronous speed at 50 Hz [rpm]	Winding circuit	Speed ratio Power	Rated operational current	Application for
2	1 Dahlander winding or 1 PAM winding	4/2 8/4	1500/3000 750/1500	△/YY	1:1.15 to 1:1.8	1:1 to 1:1.5	Nearly constant torque at both speeds
		12/6	500/1000	YY/△	e.g. approx. 1:1	e.g. approx. 1:0.9	Nearly constant power at both speeds
		6/4 8/6	1000/1500 750/1000	Y/YY	1:2.7 to 1:6	1:1.8 to 1:4	Fans, rotary compressors, pump drives
	2 separate windings	6/2 6/4 8/2 8/6 12/4 12/8	1000/3000 1000/1500 750/3000 750/1000 500/1500 500/ 750	Y/Y △/△ Y/△ △/Y	Depending on application	For higher speeds, I_e same as for standard motor, for lower speeds and small output, I_e greater than for standard motor	Constant torque or power increasing in proportion of square (fan drive)

Tab. 3.7-1
Pole-changing motors with 2 speeds

Number of speeds	Number and type of windings	Common number of poles	Synchronous speed at 50 Hz [rpm]	Winding circuit	Speed ratio Power	Rated operational current	Application for	
3	1 Dahlander winding and 1 separate winding	8/4/2 12/8/4	750/1500/3000 500/750/1500	Y/△/YY	e.g. approx. 1:2.5:3.5	e.g. approx. 1:1.7:2	Nearly constant torque at all speeds	Also with Dahlander steps YY/△ for fan drives
		8/6/4 12/8/6	750/1000/1500 500/750/1000	△/Y/YY	e.g. approx. 1:1.25:1.6	e.g. approx. 1:1.1:1.2		
		8/4/2 12/6/4	750/1500/3000 500/1000/1500	△/YY/Y	e.g. approx. 1:2:4	e.g. approx. 1:1.1:1.5		
4	2 Dahlander windings	12/8/6/4	500/750/1000/1500	△/△/YY/YY	e.g. approx. 1:1.25:1.6:2	e.g. approx. 1:1.1:1.2:1.4		
		12/6/4/2	500/1000/1500/3000	△/YY/△/YY	e.g. approx. 1:1.6:3:5	e.g. approx. 1:1.2:3:4		

Tab. 3.7-2
Pole-changing motors with 3 or 4 speeds

3.7.2 Ratings of starters for pole changing

Pole-changing motors often have, especially at lower speeds, considerably less favorable efficiency and power factors (cos φ) than standard motors. The intake current is therefore usually higher than that assigned to the corresponding power in the selection tables. Therefore the feeding contactors of the individual steps (**Fig. 3.7-1**) for all arrangements and circuit layouts (separate windings, Dahlander, PAM, phase modulation circuits) should not be rated according to the rated operational powers, but according to the rated operational currents specified by the motor manufacturer. Selection is in accordance with utilization category AC-3; for steps with inching operations, the supply contactor should be suitable for AC-4.

The star point contactor of the YY-step (K3) in Dahlander circuits, carries, depending on the circuit variation, exactly or approximately half the current of the feeding contactor for this step:

$I_{eK3} = I_{eYY}/2$ [A]

Selection is always in accordance with AC-3;

The star point contactor in a PAM circuit, because of the asymmetrical phase currents and of the harmonic content, should have the same rating as the feeding contactor of the YY step.

The rating of contactors in phase modulation circuits is based on the specifications of the motor manufacturer with respect to the rated operational current.

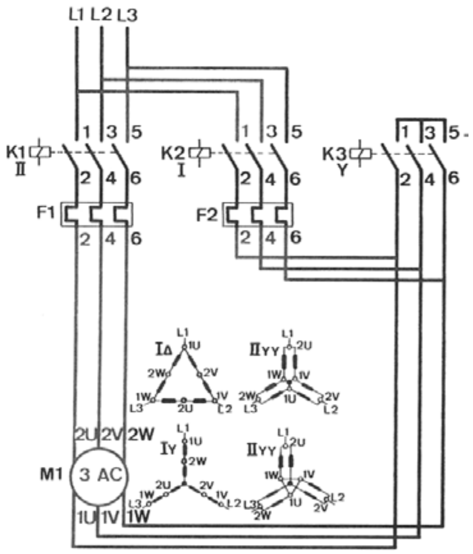


Fig. 3.7-1
Circuit diagram for motors in Dahlander or PAM circuits

For all arrangements and circuit layouts, a separate motor protective device should be provided for the thermal overload protection of the motor in each step that is adjusted to the respective rated operational current.

As a change of current direction occurs in Dahlander, PAM and phase modulation circuits when the pole number is changed in a section of the windings, a de-energized interval is necessary during switching over to prevent unacceptably high switching current surges. If the making delay of the feeding contactors of both steps is smaller than 20 ms, electrical interlocking must be performed with a switching interval (approx. 30 … 50 ms). When switching over between two separate windings, the currents that are produced are only in the range of the starting currents that the switchgear can easily cope with.

Note
Normally with multi-speed motors, a common short-circuit protection is provided for all steps, that is rated according to the largest rated operational current. It must be checked whether this short-circuit protection is also permissible for the selected feeding contactor of the smaller step. Otherwise a larger contactor should be selected.

3.7.3 Rating of the starter for steps with star-delta starting

If a winding is designed for six terminals, star-delta starting can be provided in this step. Instead of the feeding contactor, a star-delta contactor combination is required. This is rated according to the rated operational current of the relevant step.

A reduction of the starting current can also be achieved in star-delta starting in Step I with the Dahlander circuit Δ/YY (Step I: Y- Δ; Step II: YY). The circuit can be realized with only four contactors (**Fig. 3.7-2**).

The contactors are rated according to the rated operational currents I_{eI} (Step I) or I_{eII} (Step II). For the contactors K3 and K4, the higher value applies (**Tab. 3.7-3**).

Contactor	Function			Load
K1 K2	Feeding contactor Feeding contactor	Step I Step II	(Y-Δ) (YY)	I_{eI} I_{eII}
K3	Delta contactor and 1st star contactor	Step I Step II	(Y-Δ) (YY)	$0.58 \cdot I_{eI}$ and $0.5 \cdot I_{eII}$
K4	Star contactor and 2nd star contactor	Step I Step II	(Y-Δ) (YY)	Ca. $0.33 \cdot I_{eI}$ and $0.5 \cdot I_{eII}$

Tab. 3.7-3
Rating of starters for steps with star-delta starting

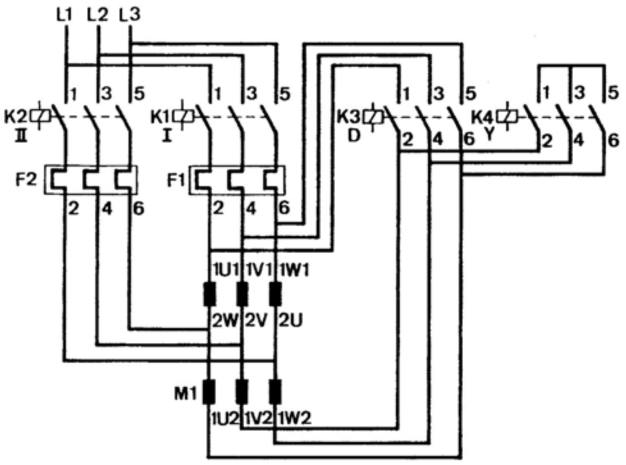


Fig. 3.7-2
2-step star-delta starter for motors in Dahlander circuit (with nine terminals), star-delta starting in Step I

3.8 Starting wound-rotor motors

With slip-ring motors (wound-rotor motors) the starting current can be limited to (1,1 ... 2,8) · I_e with high load torque and at extended starting times. This means that heavy-duty starting is also possible with supplies with poor loading capacities. See also Section **1.7.1.1**.

Slip-ring motors have rotor windings, whose three ends extend over the slip rings. When resistors are connected in the rotor circuit, the starting current and hence the torque are affected (**Fig. 3.8-1**). The starting resistors in each rotor phase are shorted stepwise by contactors during start-up.
(**Fig. 3.8-2**). In automatic starting arrangements, the contactors of the individual starting steps are controlled by adjustable time relays. In so-called Combi-motors, the rotor resistances are switched dependent of speed by centrifugal switches.

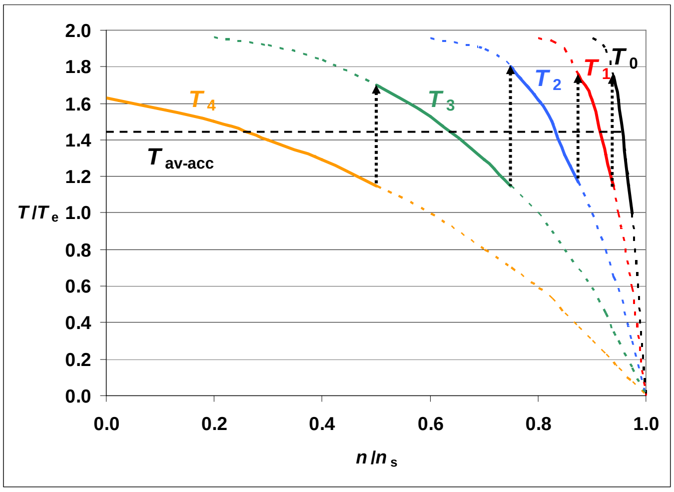


Fig. 3.8-1
Torque characteristic on starting of a slip-ring motor
T_0 … T_4 Torque characteristics of the individual starting steps
$T_{av\text{-}acc}$ Mean starting torque

A starter for a slip-ring motor can be equipped with one or more steps. On the one hand, this allows the starting torque to adjust to the working machine and, on the other, the current peaks to the supply conditions.

		Half-load starting			**Full-load starting**		
Number of resistance steps		2	3	4	2	3	4
Max. starting current	I_{max}/I_e	2.2	1.7	1.3	2.8	2.3	1.8
Min. starting torque	T_{min}/T_e	0.5	0.5	0.5	1	1	1
Starting time	s	4 … 60					

Tab. 3.8-1
Example of application: Starting motors under load

Note
With slip-ring motors, also the speed can be controlled with the resistors in the rotor circuit (resistance or slip control; e.g. for crane motors). This requires a correspondingly designed control circuit and ratings of the contactors and resistors for variable speed operation.

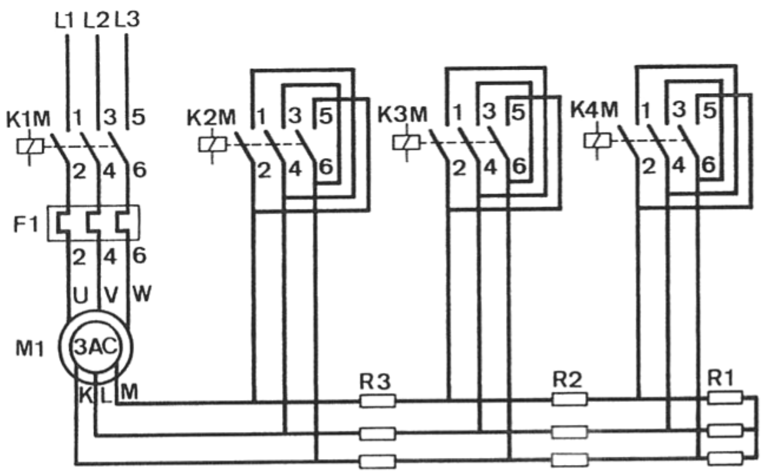


Fig. 3.8-2
Circuit diagram with three-step, automatic shorting of external rotor resistors

Ratings of the starter (start-up mode see Tab. 3.8-2)

The stator contactor K1M (feeding contactor) is selected, corresponding to the rated operational current I_e of the motor under utilization category AC-2. A distinction is made in rotor contactors between step contactors (K3M, K4M) and the final stage contactor (K2M). The rotor contactors only have to connect and conduct the current briefly. Their poles are usually delta-connected. The final stage contactor (K2M) must be designed for continuous duty AC-1; the loading is $0.58 \cdot I_{e\,rotor}$. The step contactors (K3M, K4M) operate in starter circuits in short-time duty mode. They can therefore be rated for this short-term loading or according to their making capacity.

Rating for starting with			**half-load**	**full-load**	**heavy duty**
		$I_{av\,rotor}/I_{e\,rotor}$	0.7	1.4	2.0
Stator contactor K1M		$I_{e\,AC\text{-}2}$	$I_{e\,(stator)}$	$I_{e\,(stator)}$	$I_{e\,(stator)}$
Rotor contactors (poles connected in delta)					
Final stage contactor K2M		$I_{e\,AC\text{-}1}$	$0.58 \cdot I_{e\,rotor}$	$0.58 \cdot I_{e\,rotor}$	$0.58 \cdot I_{e\,rotor}$
Step contactors	2 steps K3M		$0.20 \cdot I_{e\,rotor}$	$0.35 \cdot I_{e\,rotor}$	$0.50 \cdot I_{e\,rotor}$
	3 steps K3M, K4M		$0.18 \cdot I_{e\,rotor}$	$0.30 \cdot I_{e\,rotor}$	$0.43 \cdot I_{e\,rotor}$
	4 steps K3M … K5M		$0.15 \cdot I_{e\,rotor}$	$0.25 \cdot I_{e\,rotor}$	$0.35 \cdot I_{e\,rotor}$
Overload relay F1			$I_{e\,(stator)}$	$I_{e\,(stator)}$	$I_{e\,(stator)}$
Max. starting time per step			15 s	12 s	12 s
Max. frequency of operation (starts per hour)			120/h	30/h	12/h

$I_{e\,(stator)}$ Rated operational current of the motor (stator)
$I_{e\,rotor}$ Rated operational current of the rotor
$I_{av\,rotor}$ Mean rotor current during starting

Tab. 3.8-2
Factors for the rated operational currents of the motor for contactor selection according to the AC-2 catalog values

Permissible rated voltage for the rotor contactors

As the rotor contactors are only under voltage briefly during starting, in accordance with IEC 60947-4-1, 5.3.1.1.2 the rated operational voltage of the rotor U_{er} (rotor standstill voltage) may exceed the rated isolation voltage U_i of the contactor by 100 %. Contactors for 690 V may therefore be used up to a rotor standstill voltage of 1380 V.

3.9 Electronic soft starters

Soft starters serve for a continuous adjustment of the starting characteristic of three-phase asynchronous motors to the requirements of the load by controlling the voltage across the motor and enable for an optimum integration of the drives in process control by means of various complementary functions.

While when star-delta starters are used, the starting torque and starting current can be fix reduced to around a third, with electronic soft starters the reduction can be set within a wide range. It should be noted that the motor torque of a soft starter falls with the square of the voltage and current reduction. With the same starting current as with a star-delta starter in star connection (= 1/3 $I_{A\Delta}$), with a soft starter the motor torque falls to 1/9 $T_{A\Delta}$ in comparison to 1/3 $T_{A\Delta}$ for star-delta. See also Section 1.7.1.3.

With the conventional starting procedures such as direct on line starters, starting transformers or star-delta starters, the motor, supply and the entire drive chain is loaded by switching transients. Each switching procedure also means a rapid current change (transient current peaks) and hence generates high torque peaks in the motor. Electronic equipment with power semiconductors can prevent these transient effects and reduce the loading of power supply and drive.

The following features and options are characteristic in the use of soft starters:

- Extended setting range of the starting characteristic or selection of various starting characteristics for an optimum adjustment to the requirements of the working machine
- Infinite variable characteristic of current, voltage and torque. No transient current peaks
- Motor connection with only three lines with control in the motor supply lines
- Increased rated power of the soft starter (factor 1.73) with control in the windings circuit and motor connection with six lines
- By-passing of power semiconductors after motor start to reduce the permanent losses
- Limited number of starts per hour depending on starting conditions and thermal specifications of the soft starter
- Extended coasting to stop and braking of drives
- Crawl speed for positioning
- Diagnostic and early warning functions such as overload, underload, locked rotor etc.
- Integration in a communication network
- Integrated (motor) protection functions
- Current harmonics during the starting time by phase control
- Drives with soft starters require for maintenance work on the motor a series disconnecting device (for example disconnector switches, circuit breakers with isolating function).

Soft starters are available in a variety of different designs, each with specific technical characteristics. For the selection of a device for a specific application the technical literature of the manufacturer and its technical support have to be observed. See also IEC 60947-4-2 [5] and [17]. For specific aspects of high efficiency motors see **1.7.1.2.1**.

3.9.1 Voltage ramp versus current limitation

The basic mode of operation of soft starters is to control the voltage across the motor by phase control. Usually the phase control is performed in 3 phases and in both current half-cycles by means of triacs or antiparallel connected thyristors. Economical solutions use controlled semiconductors in only two or even only one (1) phase. The resulting asymmetries create disadvantages with respect to the available torque related to the current consumption and for example an increasing loading of the motor bearings because of torque asymmetries. The 1-phase controller corresponds to the stator-resistance starting circuit (see Section **3.5**).

The voltage across the motor can for example be controlled by

- a (selectable) voltage ramp or
- a fixed (reduced) voltage (quasi current-limiting)
- in relation to a feedback variable such as
    - motor current (current limitation) or
    - speed (start following a speed characteristic)

Depending on the method chosen, typical torque and speed characteristics for starting are produced (**Fig. 3.9-1**). When starting with a voltage ramp and especially when starting with current limitation, large acceleration torques in the range of the breakdown torque are generated towards the end of the starting period.

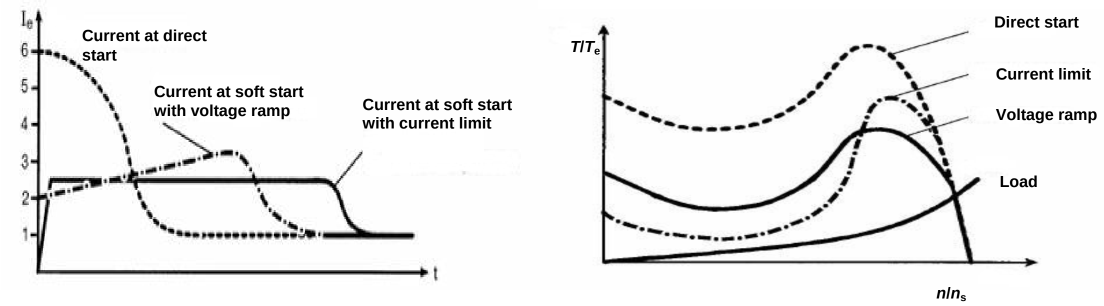


Fig. 3.9-1
Current and torque characteristics for starting

In the following a more detailed discussion of the characteristics of various available soft starter functions is presented.

3.9.2 Voltage ramp

The voltage across the motor is linearly increased during a settable time, starting from an adjustable initial value (**Fig. 3.9-2**). The starting current and the starting torque, and hence the acceleration, adjust themselves in accordance with the voltage ramp and the torque characteristic of the load. This method is especially suitable for load-free start-ups and for working machines with increasing torque requirement at increasing speed (drives with larger inertial masses, fans etc.).

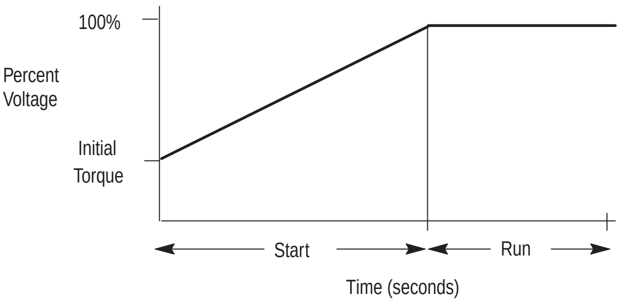


Fig. 3.9-2
Soft start with voltage ramp

For drives with variable loading at the start – for example processing machines that normally start up in a load-free condition, but which can be under load due to a fault – soft starters with two voltage ramps are available (**Fig. 3.9-3**). The initial voltages and starting times of ramps are separately adjustable and hence can be adapted to both operating states. It is possible to switch between both ramps as required.

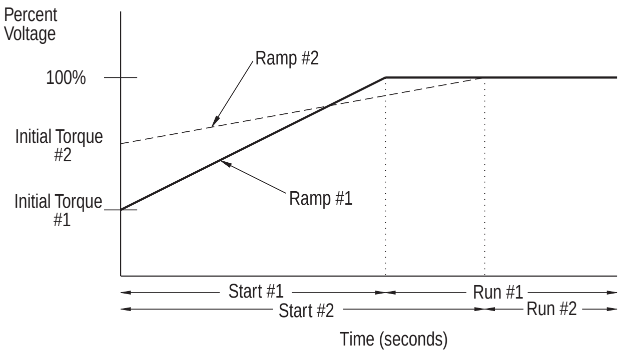


Fig. 3.9-3
Soft starter with changeable voltage ramp for various loading states at start.

3.9.3 Kickstart

Many drives have a high breakaway torque at rest, because for example bearings surfaces may generate high initial friction. This requires a short period of increased starting voltage at the beginning of the start-up. As soon as the drive begins turning, the torque requirement decreases strongly and the start can be continued with a lower voltage. Soft starters with kickstart function offer the required functionality (**Fig. 3.9-4**).

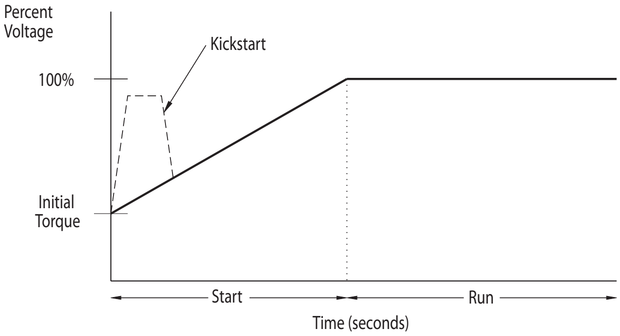


Fig. 3.9-4
The kickstart function briefly increases the voltage at the beginning of a start-up to overcome the breakaway torque of the drive.

3.9.4 Current limitation

For starts with current limitation, the starting current is adjustable. The supply load can hence be adjusted to local requirements – for example, of the electricity utility. The motor current is measured in the soft starter and the motor voltage adjusted in accordance with the set current limitation. The available motor torque falls with the square of the voltage or current. With strong current limitation, a small starting torque is thus available (**Fig. 3.9-5** and **Fig. 3.9-1**).

A simplified version just sets a fixed reduced voltage during starting.

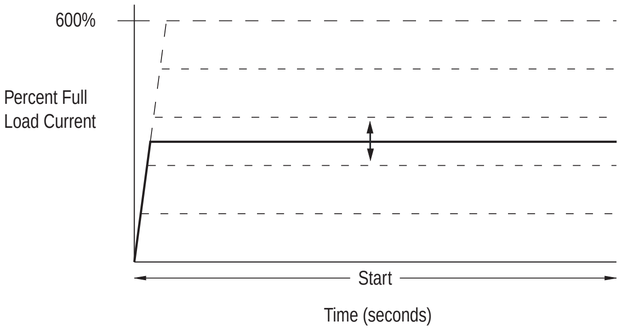


Fig. 3.9-5
During starting with current limitation the starting current can be adjusted to the supply conditions

3.9.5 Soft stop

With some drives it is desirable to also control the stoppage of the motor with a soft stop instead of a possible abrupt stop when the motor voltage is disconnected. This may for example be the case with conveyor equipment, in which sudden stopping could result in the transported goods being displaced or falling over. Soft starters with an adjustable voltage ramp upon stopping are one suitable solution. For pump controllers, see Section **3.9.6**.

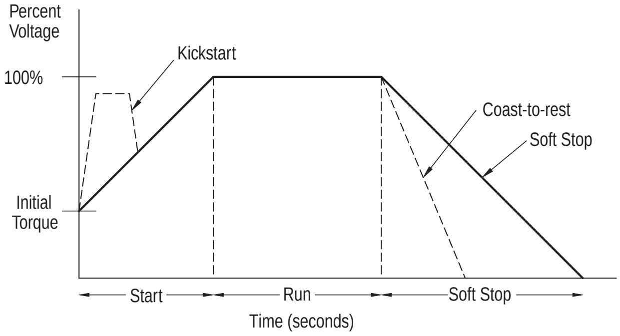


Fig. 3.9-6
Softstop function with adjustable coasting time

3.9.6 Soft starters for pump controls

In the case of rapid changes of the speed of liquids – whether at acceleration or braking – hydraulic hammer and cavitation effects can arise in large centrifugal pump systems that subject the systems to heavy mechanical stress and generate corresponding acoustic side effects. The mechanical impacts result from the fact that liquids cannot be compressed and the pressure changes in the pipe systems resulting from changes in the speed of the liquid. In the acceleration process the inertial mass of the medium to be accelerated (or decelerated) must be taken into account.

To avoid the problems described above, a slow change in the flow rate of the fluid is required during starting and stopping. During starting, this requires control of the motor voltage so that a small, constant acceleration torque matched to the specific plant requirements is produced that towards the end of starting makes a gentle transition to the operating point. The characteristics of normal soft starters with voltage ramp or with current limitation only partially fulfill these requirements. The special pump control characteristic of Rockwell Automation soft starters offer an appropriate solution (**Fig. 3.9-7**).

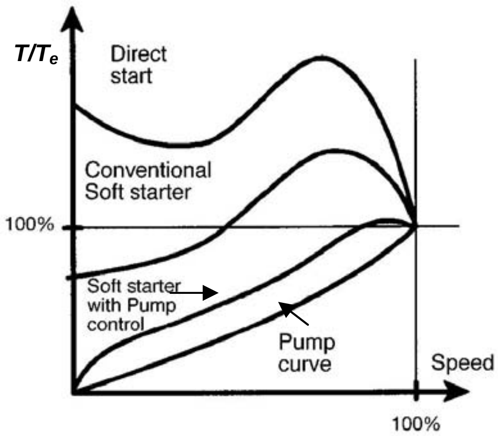


Fig. 3.9-7
The pump control function ensures that the liquid is accelerated in a gentle manner

When a centrifugal pump is allowed to naturally come to a halt, the counter-pressure of the pumped medium usually results in abrupt braking and the associated hydraulic surges, which subject the system to heavy mechanical stress. A normal soft stop by linear reduction of the motor voltage would reduce the problem somewhat but not completely remove it. The Rockwell Automation pump control function with soft stop reduces the motor voltage so that the flow-rate of the liquid continuously decreases and hydraulic impacts are avoided.

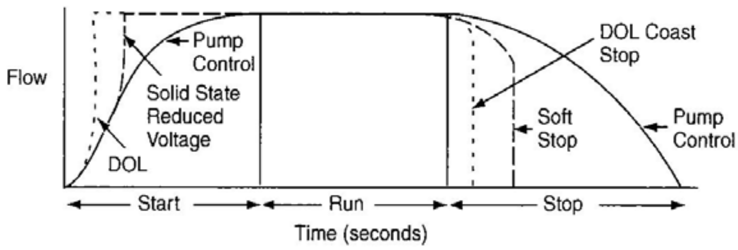


Fig. 3.9-8
The Rockwell Automation pump control function for soft starters continuously controls the flow of the medium during start-up and stopping and prevents hydraulic impacts with their adverse consequences.

3.9.7 Motor braking

For applications in which the natural coasting to a halt of the motor takes too long – for example with drives with large inertial masses – the braking function of soft starters can be useful. By appropriate control of thyristors, a braking torque is generated in the motor that results in accelerated braking. The coming to rest of the motor is detected by measurements of the back e.m.f. so that no additional devices such as standstill-sensors, contactors etc. are required. This method is not suitable for EMERGENCY STOP shutdowns.

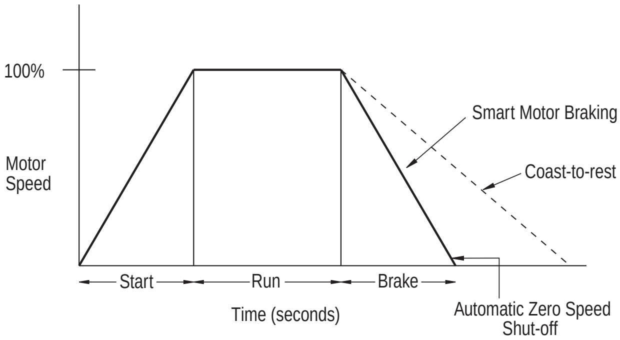


Fig. 3.9-9
The shutdown time of a drive can be reduced with the braking function

3.9.8 Positioning speed and controlled braking

Precise positioning is frequently required in engineering applications, for which the motor speed is temporarily reduced. Soft starters provide various options for accurate positioning, in one or two senses of rotation and in combination with controlled braking. See **Fig. 3.9-10** to **Fig. 3.9-12**.

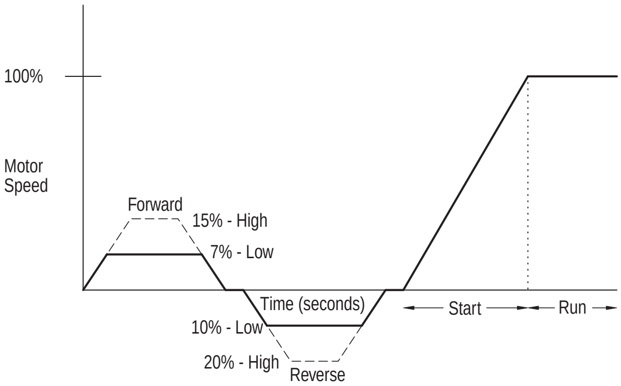


Fig. 3.9-10
Soft starters with crawl speed in both directions for positioning purposes

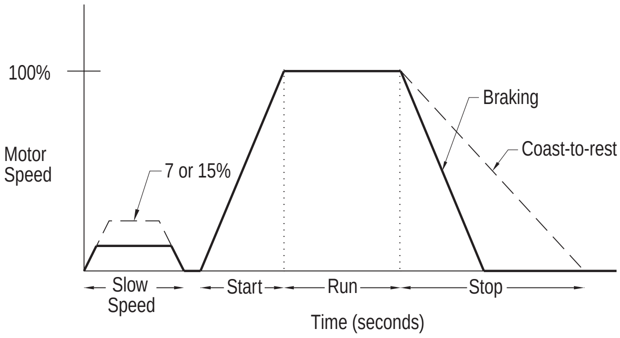


Fig. 3.9-11
Soft starters with positioning speed in one direction and controlled braking

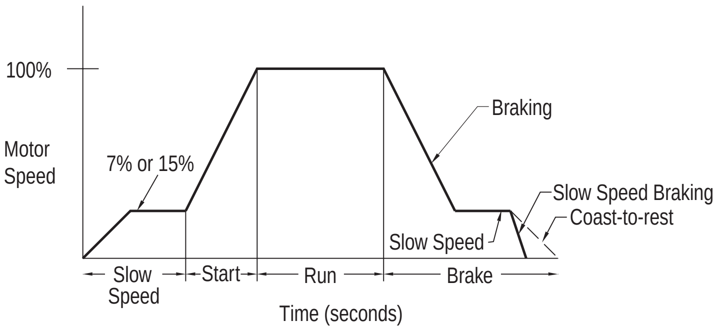


Fig. 3.9-12
The Accu-Stop™ function enables precise (accurate) positioning in one direction and precise stopping. In the braking phase, the motor is in a first phase broken until the positioning speed is reached. Complete braking happens as soon as a stop command is issued.

3.9.9 Linear acceleration and deceleration by speed feedback

Feedback of the motor speed can be used for linear acceleration and stoppage of a drive. The motor voltage is adjusted – largely independently of the torque requirement of the drive – in accordance with the speed feedback so that starting and braking follow the selected characteristic. The resulting motor current is a function of the required voltage.

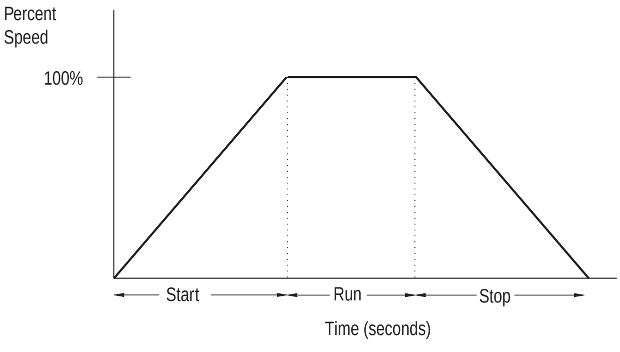


Fig. 3.9-13
Linear acceleration and deceleration of a drive by speed feedback via tachometer.

3.9.10 Direct start with full voltage

Just as with solid state (semiconductor) contactors, a start with full voltage and hence with full motor torque can be performed with soft starters.

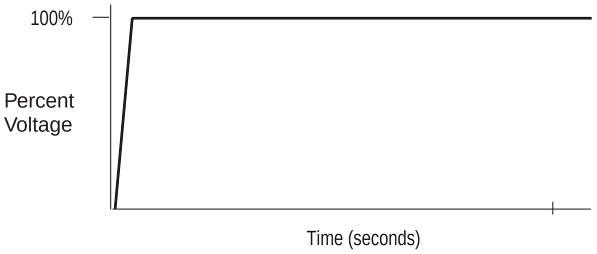


Fig. 3.9-14
Direct start with soft starters. The motor voltage is raised in a short period to the supply voltage.

3.10 Frequency converters

The main area of application of frequency converters with asynchronous motors is operational speed adjustment and control. In the lower power range of up to a few kW, they are certainly also to be considered for motor starts as an alternative to soft starters, for reasons of cost and functionality. Frequently – for example with pump and fan drives – frequency converters are applied for the optimum control of acceleration and deceleration of the drive as well as for the operational speed control, for example for energy saving purposes.

For motor starts, frequency converters offer the advantage that in the speed range up to synchronous speed the full motor torque is available. See also Section **1.7.1.4**. In addition the speed characteristic – usually a linear ramp – can be specified and set and is not a given like with soft starters where it is in a certain range a result of the motor voltage and the load characteristic (inertial mass and resistive torque).

3.10.1 Principle of operation

The basic mode of operation of frequency converters is explored below. With respect to further information – for example relating to frequency converters with vector control and slip compensation, inverters with control of the magnetic flux – refer to relevant publications of Rockwell Automation (see also Allen-Bradley Homepage www.ab.com).

The frequency converter transfers the constant voltage and frequency of the power supply first into a direct voltage. With this direct voltage it generates a new 3-phase supply for the 3-phase motor with variable voltage and variable frequency. The frequency converter draws almost only effective power (cos φ ~ 1) from the power supply if equipped with an uncontrolled rectifier. The reactive power required for the motor operation is supplied by the direct voltage intermediate circuit. Thus in most cases a supply-side power factor compensation device is not required. **Fig. 3.10-1** shows the schematic diagram.

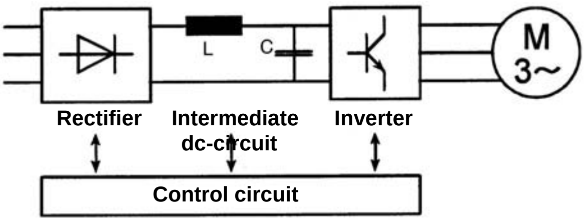


Fig. 3.10-1
Functional diagram of a frequency converter consisting of rectifier, DC intermediate circuit and inverter

3.10.1.1 Rectifier

The rectifier is connecting to the external supply and generates a direct voltage with ripple, whose amplitude (with an uncontrolled rectifier) corresponds to the peak value of the connected supply voltage ($U_e \cdot \sqrt{2}$). For drives with low power ratings (up to approx. 2.2 kW), single-phase bridge rectifiers are used for cost reasons, for larger power ratings three-phase rectifiers.

3.10.1.2 *Intermediate circuit*

The intermediate circuit stores and smoothes the direct voltage. The motor connected to the frequency converter obtains energy from it and thereby partially discharges the capacitor . This is recharged when the supply voltage is higher than the intermediate circuit voltage. The energy is thus derived from the supply, when the supply voltage is close to the maximum. This produces current peaks that should be taken into account in the selection of switchgear connected upstream (contactors or circuit breakers), as the ratings of these devices relate to sinusoidal currents. At larger power ratings (from approx. 5.5 kW), intermediate circuit chokes L are provided to extend the current flow time on the supply side and hence to reduce the current peaks.

3.10.1.3 *Inverter*

The inverter again generates a three-phase supply with the desired frequency and voltage for the connected motor. For this purpose the components of the inverter – controlled by the control-logic – connect positive and negative voltage pulses to the motor coil. Due to the high switching frequency, which may be many times above the audible range, a largely sinusoidal motor current is created in interaction with the inductances of the motor. The control of the frequency and voltage in most frequency converters is based on the principle of pulse width modulation PWM (**Fig. 3.10-2**).

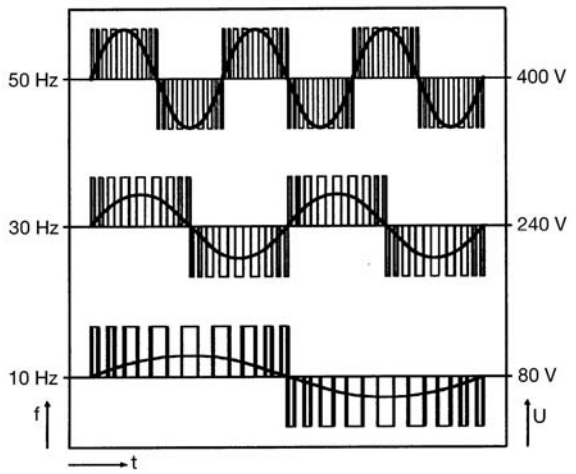


Fig. 3.10-2
Principle of pulse width modulation

3.10.2 Operational performance

Squirrel-cage induction motors require as their basic operating characteristic a so-called U/f-characteristic curve, which reduces the motor voltage in proportion to the frequency (**Fig. 3.10-3**). This is because the magnetic field in the motor is critical for the development of torque and therefore saturation of the iron core must be avoided. Such saturation would occur if at reduced frequency the magnitude of the voltage were not also reduced (constant voltage/time-area of a half cycle). In the area up to synchronous speed the drive can thus produce the rated torque (**Fig. 1.7-8** Section **1.7.1.4**).

Frequency converters are usually designed so that the motor voltage reaches its maximum value at the synchronous speed and remains constant with higher frequencies. At speeds above the synchronous speed, the available torque thus falls and the drive can be operated at constant power.

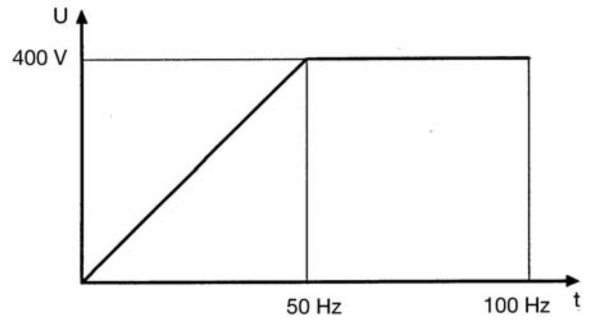


Fig. 3.10-3
U/f characteristic curve

At small frequencies (< approx. 5 Hz) the voltage drop across the internal ohmic resistances of the motor (independent of frequency) relative to that across the motor inductances (proportional to the frequency) is growing. This results in insufficient magnetization and as a consequence in a fall in torque. In order to counter this effect, a voltage boost is provided at low speeds (**Fig. 3.10-4**).

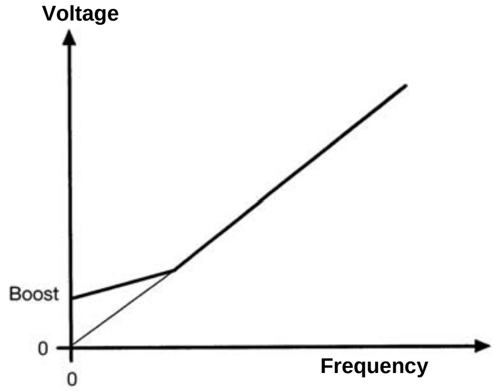


Fig. 3.10-4
Voltage boost at low frequencies to prevent a drop in torque

3.10.3 Change of sense of rotation and braking

As the rotating field in a frequency converter is generated electronically, changing the direction of rotation can be performed by means of a control command.

If the frequency is reduced when the motor is running, then the rotor turns faster than the rotating field. The motor runs in the so-called over-synchronous mode and acts as a generator. Energy is thus fed back from the motor to the frequency converter, where it is in turn stored in the intermediate circuit. This results in a voltage rise and as a consequence possibly in a protective shutdown, if the electrical energy is not removed in an appropriate manner, e.g. by means of:

- Electronically controlled dissipation of the energy via a resistance
- Feedback of the energy into the power supply by means of an inverter
- Connection of the intermediate circuits of several frequency converters and exploiting the braking energy for the operation of the total of connected motors.

3.10.4 Motor protection

Frequency converters usually have integrated electronic motor protection. No additional protection is normally required.

For special applications, for example for supplying several motors via one inverter, additional motor protection for each motor is required. If overload protective devices with bimetal tripping mechanisms are deployed for the protection of the individual motors, it must be remembered that the harmonic content of the output current from the frequency converters may possibly change the characteristic of the protective devices and the devices will also be subject to additional thermal loading. See Section **2.4.3.5**.

It should also be noted that self-ventilating motors are not suitable for continuous operation at low speeds. For such applications, external ventilation should be provided. In order to assure motor protection even at low speeds, temperature sensors, for example thermistors (PTC), must be inserted in the motor windings.

4 Protection

The protection of persons, domestic animals and property from dangers that result from the operation of electrical equipment is defined as principal elements of the safety objectives of the Directive 2006/95/EC of the European Union (Low-voltage Directive). The demand for safe operation and the avoidance of hazards and damage of all kinds is a prevailing requirement in low-voltage engineering, whether in avoiding electric shocks, dangerous overheating or the effects of electric arcs. This applies both for normal operation and in the presence of faults.

Besides the question of avoiding hazards and damage, a significant aspect of protection is to ensure the availability of electrical equipment and hence it should be seen as a productivity-ensuring measure. Each malfunction-preventing measure contributes to the safety and availability of an item of plant.

In a narrow sense protection of low-voltage devices in main circuits means

- protection of the components of the circuit themselves and
- protection of the load

The protection embraces

- protection against overload and excess temperatures and
- protection against the consequences of a short-circuit or limitation of such consequences by early and timely shutdown, but also
- recognition of impending malfunctions before a protective shutdown actually occurs, such as for example overloading of a drive, asymmetrical supply or lack of flow of the medium in submersible pump motors.

While protection primarily aims at the prevention of damage, this is also always connected with the question of utilization of the equipment. Protective shutdowns before they are actually necessary, while they may be compatible with the safety objectives, represent a disruption to operations and can prevent full exploitation of production equipment. In this way, protective measures always have an economic significance and increased expenditure for high quality protection can be justified from this point of view.

4.1 Protection requirements

The key protection requirements for low-voltage installations are

- protection against electric shock
- protection against overload / excess temperature
- protection against the consequences of short-circuits and ground faults

The following discussion relates specifically to the protective functions of low-voltage switchgear in accordance with IEC 60947.

4.1.1 Protection against electric shock

Protection against electric shock is achieved by a multi-level approach:

- Protection against direct contact
- Protection against indirect contact
- Complementary protection

4.1.1.1 Protection against direct contact

Protection against direct contact with live components is achieved in electrical installations by encapsulation. IEC 60439-1 stipulates at least protection type IP2X or IPXXB for switchgear assemblies. Switchgear assemblies to which unskilled persons have access must in accordance with IEC 60439-3 have a degree of protection of at least IP2XC. National regulations must always be respected.

For switchgear itself, in some countries there are regulations with respect to the accessibility of live components. This has resulted in a de facto standard for the devices that largely fulfill the requirements of protection type IPXXB (finger safe). This considerably reduces the risk of an electric shock by direct contact even when work is being carried out in switchgear assemblies. For devices with larger rated currents, often protective covers are required for complying with IPXXB.

4.1.1.2 Protection against indirect contact

Protection against indirect contact ensures that even in the event of failures – for example in case of a conductive connection between a pole conductor and a metallic component – no dangerous touch voltages (≥ 50 V a.c. or ≥ 120 V d.c.) can arise or that such voltages in are disconnected in a very short time before a risk of personal injury can result. Usually such protection is achieved by grounding measures and short-circuit protection equipment such as fuses, miniature circuit breakers or circuit breakers, as the fault currents in such cases can be very large.

Protective Extra Low Voltage (PELV) and Safety Extra Low Voltage (SELV) are also suitable means of protecting from indirect (and direct) contact. They are frequently used in electronic circuits. See also Section **2.3.11**.

If the lines are long between the short-circuit protection device and the location of fault, the fault current can fall below the response level of the short-circuit detecting device (for example of a circuit breaker for motor protection) due to the damping effect of the line. For fix installed loads (for example motors) the requirement is that the contact voltage on the motor-case – if ≥50 V a.c. or ≥120 V d.c. – must be switched off within 5 seconds. To test compliance with these conditions at the stage of engineering, the current in the event of fault has to be calculated taking into account all loop impedances (incl. for example the internal resistance of the bimetal tripping mechanism of any motor protective circuit breakers). The prospective tripping time should be checked based on the overload characteristic of the protective device (**Fig. 4.1-1**). The manufacturer of protective devices offer advice on applications in such cases.

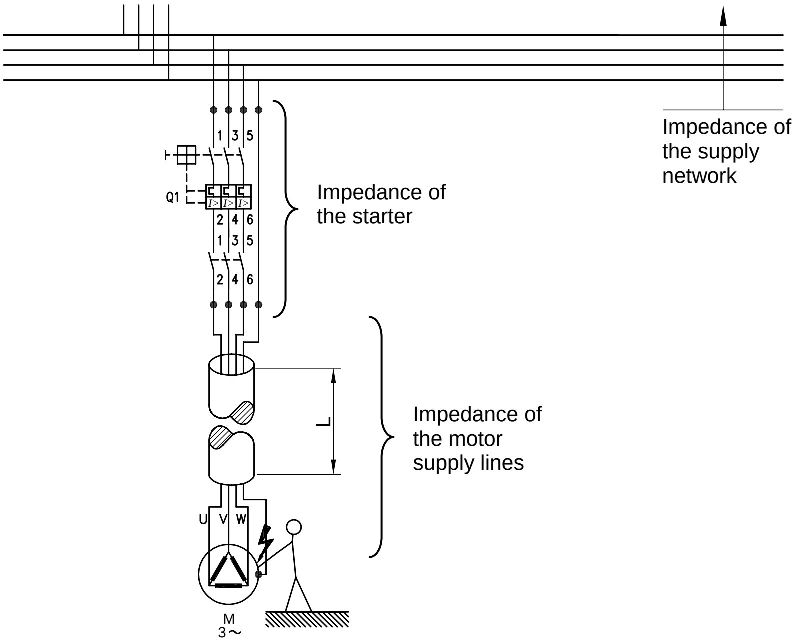


Fig. 4.1-1
When the cables to the load are long, impedances in the circuit can, in the event of a short-circuit in the load, cause the fault current to fall below the tripping level of the short-circuit detector. It must then be ensured that the thermal release mechanism clears the fault within 5 seconds.

4.1.1.3 *Complementary protection*

The complementary protection effectively provides a third safety net with respect to the protection against electric shock and offers protection from direct and indirect contact.

Residual current protection equipment with response levels ≤ 30 mA shut down touch currents before they reach a dangerous level for persons.

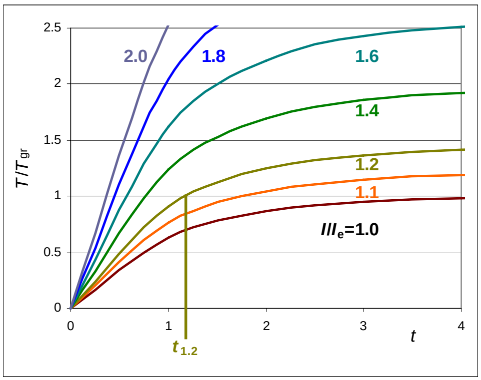
Voltage equalizing measures reduce the voltage of accessible parts in the event of a fault.

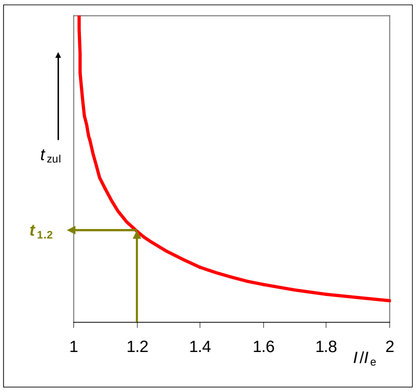
4.1.2 Protection against overload and excess temperature

Components can be thermally overloaded if they are subjected to operational overcurrents for extended periods. This can be due to unexpected overloading or because the rated load capacity of electrical equipment, such as the rating of motors or lines, is too low. Overload currents do not lead to immediate danger or immediate outage. However they heat the electrical equipment above the rated temperatures for continuous duty and reduce the life span of its insulation.

The higher the overload current is, the faster the permissible limit temperature will be reached, and the shorter is the permissible loading time (**Fig. 4.1-2** a). The limiting loading curve is obtained by entering the times of permissible loading in a current-time diagram (**Fig. 4.1-2** b).

The task of the overload protective device is to allow operationally occurring overcurrents but to switch them off timely before the permissible loading time is exceeded.





a) Heating at loading with rated current ($1.0 \cdot I_n$) and at various overcurrent levels ($1.2 \cdot$, $1.5 \cdot$, $1.7 \cdot$, $2 \cdot I_n$)

b) Limiting loading curve

T_{gr} Rated limit temperature
T temperature

t time
t_{zul} permissible loading time

Fig. 4.1-2
Temperature rise characteristic of a body at various loading levels and limit loading, when its limit temperature is not exceeded

4.1.2.1 *Different loading curves of various kinds of electrical equipment*

Various kinds of electrical equipment such as conductors in comparison to motors or electrical equipment of the same kind with different rated powers have different limit loading curves due to their differing masses. Thus a conductor with a small cross-section reaches its limit temperature much quicker than a large motor with compact windings that are imbedded in the iron core.

These differences are also important for the performance at changing load, when heating phases are followed by cooling phases and the final temperature of one phase represents the initial temperature of the next phase. Deviations in the replication of the thermal performance of the protected object by the protective device can thus add up and lead to premature tripping or failing of the protection (**Fig. 4.1-3**).

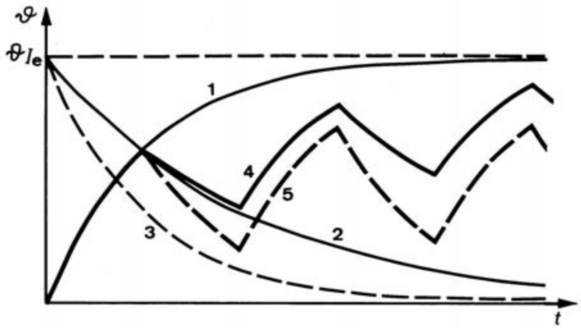


Fig. 4.1-3
At intermittent operation of self-ventilating motors the simulated temperature rise of a thermal relay lags behind the actual motor heating as the rate of cooling of a stationary motor slows down.
δ Temperature
1 Heating characteristic of motor and thermal relay
2 Cooling characteristic of the motor
3 Cooling characteristic of the thermal relay
4 Windings temperature in the motor
5 Windings temperature as simulated by the thermal relay

This variety in protective requirements has given rise in practice of technical feasibility and cost effectiveness to a classification of protection characteristics and protective devices that has proved itself in a large number of applications and over many decades. This standardization is laid down in the relevant standards and offers practical and economic solutions without claiming to be tailor-made for every individual case.

This results in the fact that different protective devices are assigned to different application areas. Thus fuses are suitable for the thermal (and short-circuit protection) of lines but not for the thermal protection of motors.

4.1.2.2 Protection in continuous duty and at transient loads

The primary protection requirement with respect to overload/excess temperature is the prevention of long-term overloads and excess temperatures that result in accelerated ageing and in consequence to premature degradation of the insulation.

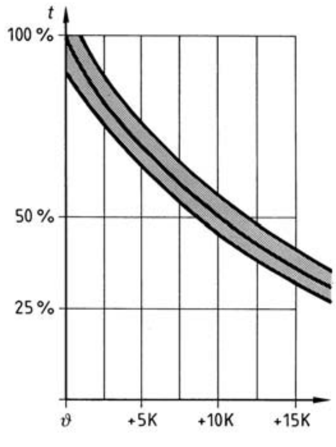


Fig. 4.1-4
Reduction of the average life span of motor windings at overtemperatures

Current-measuring protective devices such as thermal (bimetal) or electronic motor protective devices comply with this requirement by calibration of the tripping current for continuous duty (ultimate tripping current). The tripping current level can be matched to the object to protect (motor) by setting on a scale. Correspondingly, for the protection of lines, there are for example fuses or miniature circuit breakers with defined rated currents that are adapted to the available conductor cross sections.

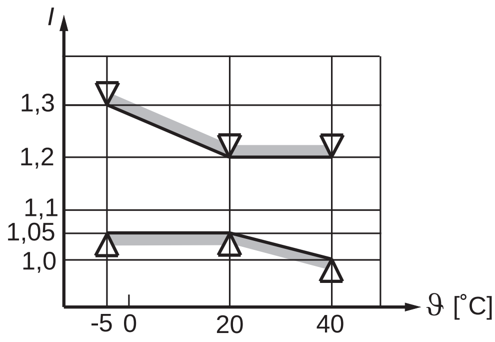


Fig. 4.1-5
Tripping tolerances for temperature-compensated overload relays for motor protection under IEC 60947-4-1
I Overload as a multiple of the set current
δ Ambient temperature
△▽ *Limit values under IEC 60947-4-1*

Current setting

Usually, the motor protection relay should be adjusted to the rated current of the motor, for star-delta starters to 0.58 · I_n, as the measurement is made in series to the motor windings.

If the coolant temperature is over 40 °C, then the power of the motor should be reduced and the current setting on the motor protection relay should be adjusted accordingly. If the motor manufacturer does not specify otherwise, the values of **Tab. 4.1-1** can be used for correction.

Coolant temperature °C	30	35	40	45	50	55	60
Correction factor (k_1)	1.08	1.04	1	0.95	0.9	0.85	0.8

Tab. 4.1-1
Typical values for the correction factor for the current setting ($k_1 \cdot I_n$) on motor protection relays in relation to the coolant temperature of the motor

At altitudes of installation over 1000 m above sea level the permissible motor loading is reduced and hence also the setting of the motor protection relay has to be adjusted accordingly. If the motor manufacturer does not specify otherwise, the values of **Tab. 4.1-2** can be used for correction. If other coolant temperatures occur and at the same time the motor is operated at high altitudes then the product of both factors should be taken into account when choosing the current setting on the motor protection relay.

Installation altitude above sea level [m]	≤ 1000	1500	2000	2500	3000	3500
Correction factor (k_2)	1	0.97	0.94	0.90	0.86	0.82

Tab. 4.1-2
Typical values for the correction factors for the current setting ($k_2 \cdot I_n$) for motor protection relays in relation to the operating altitude of the motor

Transient performance

The simulation of the thermal characteristic of the protected object at transient load conditions by current-measuring protective devices is always an approximation and dependent on the complexity of the protected object with respect to heating and cooling. Thus for example a bimetal relay is much simpler in design than a motor and even complex electronic protective devices only roughly approximate the characteristic of the protected object. Allowance is made for this fact by precautionary making the protective device react more quickly as would be required with respect to the extent of risk to the protected object. This means playing safe and "over protecting" the protected object with the result that its actual load capacity cannot be used in full. In most cases this is anyhow not necessary.

An example is motor start-ups. They are usually so short that normal protective relays of class 10 or 10 A (**Tab. 4.1-3**) can be used, although motors in most cases allow for longer starting times without problems.

Thermal memory of electronic protective relays

Thermal protective relays, such as for example bimetal relays, have a thermal memory that approximately simulates the cooling of motor windings. As bimetal relays do not require any voltage supply, the thermal memory is assured even in the event of a voltage outage. This means that for example after a short voltage outage (with the associated motor shutdown), the bimetal strips are still warm and the next time that the motor starts it is protected against thermal overload.

Electronic protective relays require a power supply to function. This can be obtained via current transformers from the measuring circuit or via a power supply unit that is for example connected to the control voltage supply. Electronic protective relays can be designed so that they have a thermal memory or that they immediately are reset to "cold" when the motor to be protected is switched off. Relays without thermal memory must be declared as such by the manufacturer (marking on the device). For relays with a thermal memory IEC 60947-4-1 requires a test and stipulates in this regard the following minimum requirements:

- Preheating with I_e
- Disconnection of the current during $2 \cdot T_p$ (double time of trip class; for example 20 s for class 10)
- Loading with $7.2 \cdot I_e$
- The relays must trip within 50 % of T_p (for example 5 s for class 10)

Motor protection with heavy-duty starting

While the starting current of a motor ($I_A \approx 4 \dots 8\ I_n$) is determined by its design, the starting time t_A depends on the load (inertial mass and resistive torque). In accordance with **Fig. 4.1-6** reference is made to heavy-duty starting, if the starting time – depending on the starting current – is several seconds. Normal thermal motor protection relays are in such cases usually overloaded and will trip during start-up.

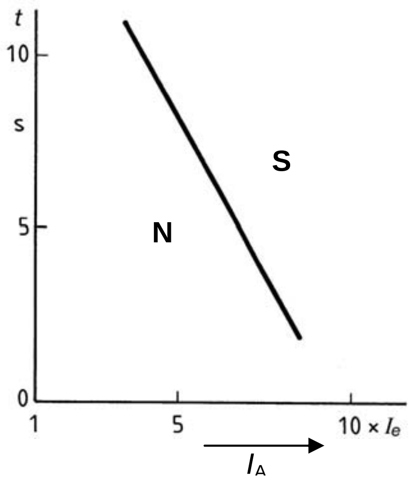


Fig. 4.1-6
Heavy-duty starts are classified as starting times above the limit curve (typical values)
t = *starting time*
I_A = *starting current (≈ 4 ... 8 I_n)*
N = *normal starting conditions*
S = *heavy-duty starting*

IEC 60947-4-1 provides various trip classes (**Tab. 4.1-3**) for motor protection relays in order to adapt the protective devices to the starting conditions. The limiting values with tighter tolerances "E" have been introduced for electronic protective relays. Under heavy-duty starting conditions, electronic motor protective devices can be advantageously used since they can be adjusted to the specific starting conditions (see Section **4.2.4.2**). Solutions with thermal motor protection relays and saturation current transformers, bypassing of the protective relays during starting or use of a separate protective relay for the starting are thus obsolete.

It should be noted that with heavy-duty starting, it may be necessary to increase the cross-section of wiring of the starter components and of the motor. Thus IEC 60947-4-1 stipulates in the test conditions for protective relays of Classes 10, 20, 30 and 40 and for protective relays, for which a maximum tripping time > 40 s is specified, that the tests - among other things - must be performed with conductor cross sections suitable for 125 % of the current setting on the relays.

Trip class	Tripping time at 7.2 · I_e (normal tolerance) s	Tripping time at 7.2 · I_e (tighter tolerances „E") s
2	-	$T_p \leq 2$
3	-	$2 < T_p \leq 3$
5	-	$3 < T_p \leq 5$
10A	$2 < T_p \leq 10$	-
10	$4 < T_p \leq 10$	$5 < T_p \leq 10$
20	$6 < T_p \leq 20$	$10 < T_p \leq 20$
30	$9 < T_p \leq 30$	$20 < T_p \leq 30$
40	-	$30 < T_p \leq 40$

Tab. 4.1-3
Trip classes of overload relays in accordance with IEC 60947-4-1 am 2. The trip class number stands for the longest permissible tripping time at 7.2 · I_e from a cold state.

Motor protection in hazardous areas

Motor protective devices for the protection of motors of the protection type "Increased Safety" EEx e must comply with the standards and regulations like discussed in Section **2.4.7**. The motor protective devices themselves are not explosion-protected and may therefore not be installed in the hazardous zones.

4.1.2.3 Overload and overtemperature protection by measurement of current and measurement of temperature

The obvious way to identify excess temperatures is by directly measuring them. Thus all factors are included that influence the temperature at the measuring location – e.g. the ambient temperature that frequently varies within a wide range and that is often not taken into account by current-measuring protective devices or obstructed cooling. When measuring the current, a simulation of the temperature rise is carried out and a worst-case scenario is created with respect to the ambient temperature conditions. It is thereby assumed that the ambient temperature of the protected object corresponds to the maximum permissible temperature. This reference temperature is defined for motors in accordance with IEC 60034 to 40 °C at site altitudes of up to 1000 m.

Temperature sensors (for example PTC) are frequently being used for measuring the temperature of motor windings and have proven its worth in practice. The effect of measurement delays at very rapid temperature rises (for example with a locked rotor condition) is only adverse for thermally especially critical motors (for example submersible pump motors) or large machines in which the rotor is the thermally critical component (**Fig. 4.1-7**). However temperature measurement is not always appropriate, possible or at least it can be very expensive. In rotor-critical motors for example, the measurement from the rotor to the stator is very costly. Line conductor protection via temperature measurement is hardly practical for various reasons.

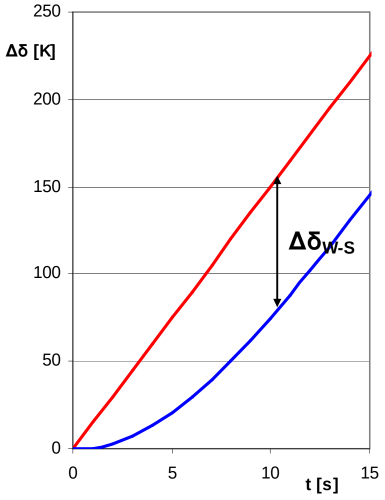


Fig. 4.1-7
Thermal delay of a PTC sensor integrated in the stator coil with rapid temperature rises (for example with a locked rotor)

$\Delta\delta$	=	*Temperature difference above the coolant temperature of 40 °C*
$\Delta\delta_{W-S}$	=	*Temperature difference winding – sensor*
t	=	*Time in s*

The measurement of the load current by the protective device has proven reliable and economic in the majority of normal applications, even if the full exploitation of the actual load capacity of the electrical equipment is often not possible. Current measurement offers specifically for the protection of motors the option for functions that cannot be measured via the temperature as the current contains important information about the operating status of the motor and its exposition to potential damage. Temperature measurement by means of sensors integrated in the windings is usually used as a complementary method.

4.1.2.4 Protective functions

Due to their differing modes of operation, various types of protective devices offer a variety of functions and properties. **Tab. 4.1-4** provides a summary of the most important protective functions and their availability by technology, specifically considering motor protection.

Function	Current-measuring		Temperature-measuring	
	Bimetal	Electronic	PTC sensor	Linear sensor
Protection against overload and overtemperature in continuous duty	X	X	X	X
Protection against overload and overtemperature under special (e.g. obstructed) cooling conditions	---	---	X	X
Protection against overload / overtem-perature during starting	X incl. rotor-critical machines	X incl. rotor-critical machines	X excluding rotor-critical and thermally very fast-reacting machines	X excluding rotor-critical and thermally very fast-reacting machines
Protection at intermittent service	(X) depending on the operating cycles	X relays with switching-over to cooling time constants	X excluding rotor-critical and thermally very fast-reacting machines	X excluding rotor-critical and thermally very fast-reacting machines
Stalling protection	(X) via thermal protection	X undelayed	(X) via thermal protection	(X) via thermal protection
Starting-time monitoring	(X) via thermal protection	X	(X) via temperature	(X) via temperature
Underload prot.	---	X	---	---
Ground fault prot. [1)]	---	X	---	---
Short-circuit prot. [1)]	---	X	---	---
Phase-loss protection	X accelerated	X short delay	X via temperature	X via temperature
Asymmetry protection	---	X	(X) via temperature	(X) via temperature
Temperature-rise display	---	X	---	X
Warning before tripping	---	X	(X) with 2. set of sensors	X
Display time to trip	---	X	---	---
Start interlocking	---	X	(X) with additional set of sensors	X
Current monitoring	---	X	---	---
Protection of EExe motors	X	X	X	X
Control switching-over Y-D	---	X	---	---
Communication	---	X	---	X
Settings	Current	All parameters	---	Response temperature(s)

Tab. 4.1-4
Summary of functions of protective relays with focus on motor protection
X available (possibly as option)
(X) limited or restricted availability
--- unavailable
[1)] Disconnection via circuit breaker

The listed functions are discussed in more detail below.

4.1.2.4.1 Protection during starting, monitoring of starting time, start interlocking

In addition to protection in continuous duty, protection during motor starting is a central requirement because of the high starting currents. Protective response of the protection device before the motor danger zone is reached is advantageous as long as normal starting is not prevented. In the case of disturbances (for example locked rotor) the motor would not be loaded up to its thermal limit and the waiting time for cooling down after removal of the cause of the fault is reduced. Temperature-measuring protective equipment does not switch off until the trip temperature is reached, while current-measuring protective devices may trip earlier depending on their trip characteristic (with electronic relays often adjustable).

Electronic relays offer the option to monitor the starting time. The thermal protection can in this case be set to the danger limit of the motor, while the starting time monitoring warns or switches off, if the motor current has not fallen to the operating level in the expected time.

With prolonged start-ups in which the thermal capacity of the motor can be largely exploited, it may be desirable to not allow starting until the necessary thermal reserve is available. Such a start interlocking can be implemented with electronic relays that have an output that displays the simulated heating of the motor, or with temperature sensors. Analog sensors (for example Pt 100) offer the possibility of setting the desired temperature threshold; in sensors with a fixed threshold of response (for example PTC) a second sensor unit is required with the desired response temperature.

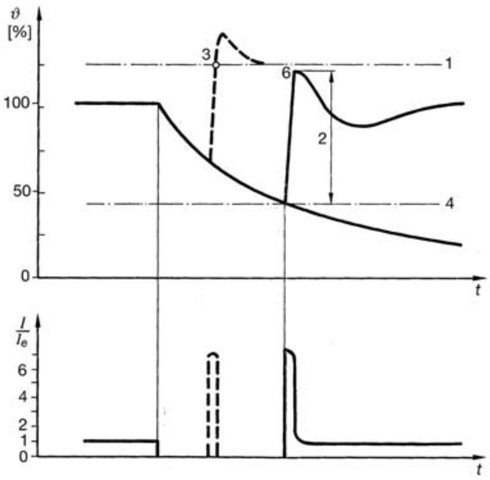


Fig. 4.1-8
Unsuccessful starts can be avoided if the motor start is not enabled unless the motor has an adequate temperature-rise reserve.
1 Trip temperature
2 Temperature rise during starting
3 If the windings temperature is too high, the start is not enabled as it would lead to tripping
4 Temperature threshold, under which starts are enabled
6 Temperature at the end of a starting that just did not lead to tripping

4.1.2.4.2 Asymmetry protection

When asynchronous motors are supplied with an asymmetrical voltage – with the extreme case of loss of a phase – a thermal risk results because of the differing windings currents that are caused by the negative sequence system of the supply voltage. An asymmetric supply voltage contains such a negative sequence system, that turns in the opposite direction to the normal symmetrical supply, the positive sequence system, and hence has a frequency of around 100 Hz relative to the rotor of a running motor. These voltage components create in the rotor – and hence also in the stator – a comparatively large current, similar to the conditions during motor start-up, when the 50Hz/60Hz supply voltage with the rotor at standstill generates the high starting current. The current distribution in the rotor due to the high frequency results in heavily increased losses that can in the long term thermally endanger the motor even at relatively small voltage asymmetries. In accordance with IEC 60034-1 the rated data of motors are based on a max. 1 % voltage asymmetry. With larger asymmetries the motor loading should be reduced (**Fig. 4.1-9**).

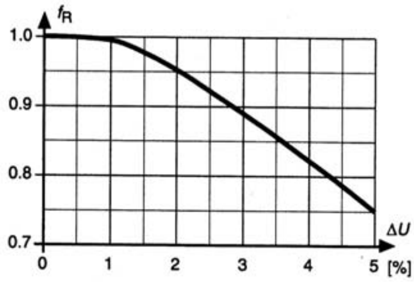


Fig. 4.1-9
Power reduction as a consequence of voltage asymmetry
f_R Reduction factor for motor power
ΔU Voltage asymmetry [%]

4.1.2.4.3 Phase failure protection

Star-connected motors

Small to medium-sized (stator-critical) motors in star configuration are in generally not endangered by phase-loss. In accordance with **Fig. 4.1-10**, the currents in the motor windings both in normal operation and with loss of one phase are the same as the currents in the external conductors. The protective device also measures the current flowing through the windings in the event of the failure. In both windings through which the current flows, because of the increasing current at constant mechanical motor load, an increased power dissipation results. With the third – de-energized – winding a temperature compensation occurs, so that a current-measuring protective device would release in time in event of an overcurrent.

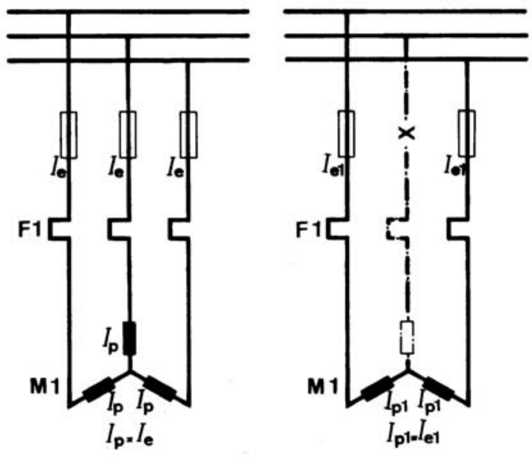


Fig. 4.1-10
Motor in star configuration under normal supply conditions and with phase failure

Motors in delta configuration

In the delta configuration and in normal operation, the windings currents I_P are smaller than the currents I_e in the external conductors by a factor 1/√3 = 0.58. If a phase is lost (**Fig. 4.1-11**) the current increases in one winding by around 15 % – assuming the current in the external conductors remains constant ($I_{e1} = I_e$). In the two other windings that are now connected in series, the current falls to a 1/√3 times smaller value. In comparison to symmetrical operation, the protective relay measures a current that is too low for the winding that lies between the healthy phases, which can cause a thermal overload in this winding without the protective device responding. Heat exchange between this and the other windings that carry less current reduces the danger of a thermal overload in small motors up to around 10 kW.

In a real application, the mechanical load of the motor remains constant with the outage of one phase. As the electrical power is only provided from two pole conductors, the current in the two external conductors (I_{e1}) and the phase currents (I_{P1}, I_{P2}) in comparison to the case described above is a factor larger. This factor depends on the load of the motor. The relationships are as represented in **Fig. 4.1-12**.

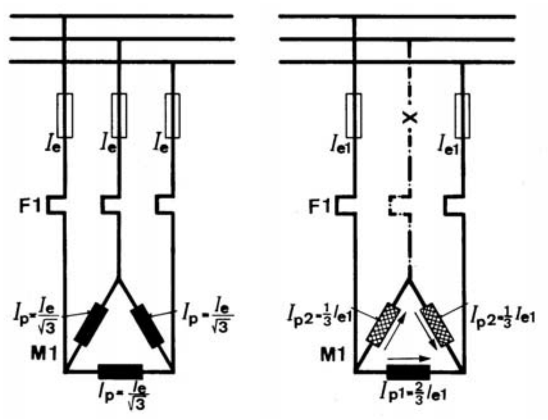


Fig. 4.1-11
Current distribution in delta-connected motors in normal operation and with loss of one phase

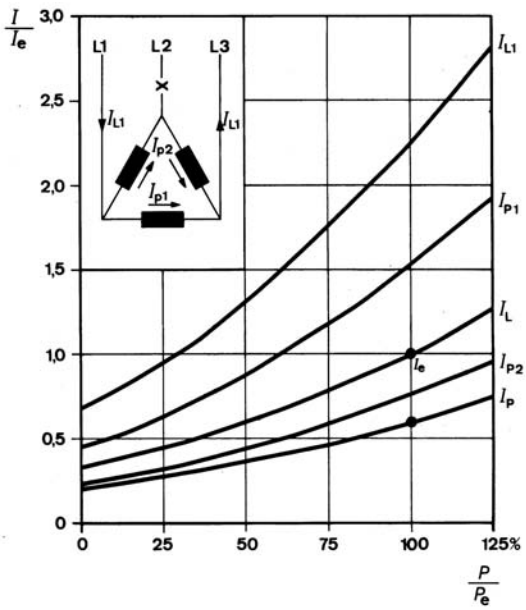


Fig. 4.1-12
Phase loss of a delta-connected motor. Current flow with symmetrical supply and with phase loss as a function of the load

IEC 60947-4-1 defines the requirements on the performance of motor protective devices in the event of a phase loss (**Tab. 4.1-5**). For high quality motor protection temperature-compensated devices with phase failure protection are standard.

Type of overload relay	Multiples of current setting		Reference ambient air temperature
	A	**B**	
Thermal, compensated for ambient air temperature variations or electronic **Not phase loss sensitive**	3 poles 1.0	2 poles 1.32 1 pole 0	+20 °C
Thermal, not compensated for ambient air temperature variations **Not phase loss sensitive**	3 poles 1.0	2 poles 1.25 1 pole 0	+40 °C
Thermal, compensated for ambient air temperature variations or electronic **Phase loss sensitive**	2 poles 1.0 1 pole 0.9	2 poles 1.15 1 pole 0	+20 °C

Tab. 4.1-5
Tripping threshold values of three-pole overload relays with phase-loss protection in accordance with IEC 60947-4-1 am 2
*Column **A** No tripping within 2 hours (from cold state)*
*Column **B** tripping within 2 hours subsequently to the test according Column A*

Protective shutdown with the outage of a supplying phase is desirable to prevent damage to the motor and because continuation of normal operation is in any case impossible. A motor start with phase-loss is not possible, because three-phase induction motors do not develop any torque with phase loss at standstill.

Phase failure protection is largely standard with current-measuring protective relays. Tripping is usually accelerated (bimetal relay with sensitivity to phase failure) or briefly delayed (electronic relays). Complex electronic protective relays are often equipped with a sensitive asymmetry protection that takes into consideration the risk to the motor from the negative sequence system.

Protective equipment with sensors in the windings protects against overheating of the windings due to phase-loss and also to asymmetry. As they measure the temperature in the stator windings, they are not able to detect a specific risk to the rotor. They do not respond until the threshold temperature is reached.

4.1.2.4.4 Stalling protection

In applications, in which drives are stalling from normal operation or can be heavily overloaded (for example stone crushers, calenders), it may be required that the application immediately shuts down or issues a warning signal when a high load occurs before the thermal protection is acting. This is to protect the mechanical transmission elements or to early rectify the fault and prevent long waiting times after a thermal protective shutdown.

Electronic relays measure the motor current and often offer a stalling protection function with an adjustable threshold with respect to the current and trip delay. In order to make motor start-up possible, stalling protection is not activated until after start-up.

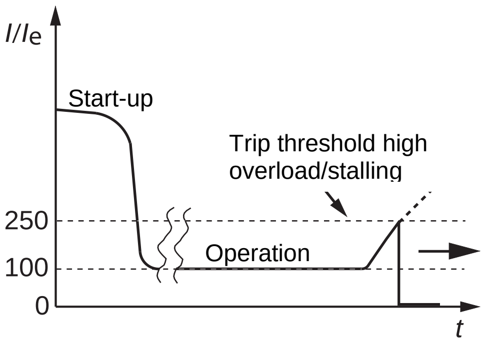


Fig. 4.1-13
Stalling protection recognizes high overloads and enables rapid intervention or protective shutdown

4.1.2.4.5 Underload protection

Motors that are cooled by the conveyed medium itself (for example submersible pumps, fans), can become overheated as a result of underloading when the volume of the medium is absent or reduced (obstructed filters, closed slides). These machines are often installed in inaccessible places. The consequences are long repair time and correspondingly high costs.

When the current intake falls below a certain level, also a mechanical fault in the system may be indicated (torn conveyor belts, damaged fan rotors, defective clutches, broken shafts or worn down tools). Such conditions do not endanger the motor, but result in production outages.

The underload protection monitors the current intake of the motor and by rapid recognition of an underload, helps to keep any disruptions and damages as small as possible.

4.1.2.4.6 Automatic switching-over during start-up

Monitoring the current consumption of a motor for falling below a defined threshold can also be used for automatic control of switching-over of star-delta starters or auto transformer-starters. The relay recognizes by the magnitude of the current, when the first phase of the starting process has ended and immediately initiates switching-over to the second phase. Thus start-ups can be kept to an optimally short length – even under changing starting conditions.

4.1.2.4.7 Ground fault protection

Damage to the insulation of motors is frequently caused by high voltage spikes. The sources may be switching transients from the supply network, capacitor discharging, power electronics devices or lightning strikes. Other causes are ageing and continuous or cyclical overload as well as mechanical vibrations and foreign particles. In most cases, insulation damage results in shorting against the grounded parts of the machine. In grounded supply systems, the ground currents can quickly reach very high values.

The prompt detection and protective shutdown of a ground fault limits the extent of the resulting damage and helps to reduce outages and repair costs.

A relatively simple ground fault protection method measures the zero sequence current component of the current transformer-secondary currents (“Holmgreen”-circuit, **Fig. 4.1-14**). Because of the tolerances of current transformers and of the influence the 3rd harmonic a sensitivity of 10 % can be achieved at best, typically around 30 %. This method is thus also limited to application in solid grounded networks.

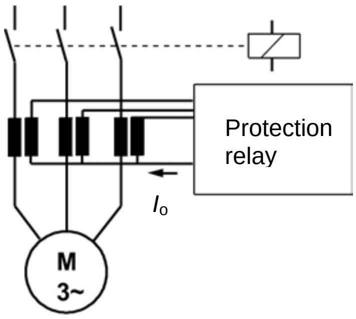


Fig. 4.1-14
In the Holmgreen circuit, the current I_o is measured in the common return conductor of the current transformers. Because of the inaccuracy of the c.t.'s, the sensitivity is low.

Higher sensitivities can be achieved with core balanced current transformers (principle of the residual current protection devices, **Fig. 4.1-15**).

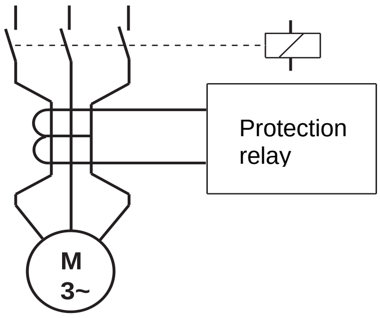


Fig. 4.1-15
In core balanced current transformers the iron core encloses all conductors leading to the motor like in a residual current protection switch. High ground fault sensitivities can thus be achieved.

The shutdown of ground faults should be by means of a circuit breaker, as ground currents frequently exceed the switching capacity of contactors. When normally shutting down via the contactor, exceeding of its switching capacity must be prevented (inhibit). In this case, the upstream short-circuit protection device takes over the job of clearing the fault.

4.1.2.5 Display, warning and control functions

In addition to the protective functions electronic motor protection relays provide valuable information for monitoring and optimum operation of drive installations. The below functions are possible:

- Display of motor current flowing
- Display of overloads
- Display of the temperature status of the motor
- Prewarning before protective tripping
- Display of time to protective tripping (at constant load)
- Control of the drive load (for example stone crushers, calenders) for optimum motor temperature and hence maximum production
- Display of the required cooling time before the next start-up
- Switching of star to delta as soon as the starting current falls
- Closing the bypass of pumps or fans immediately after starting
- etc.

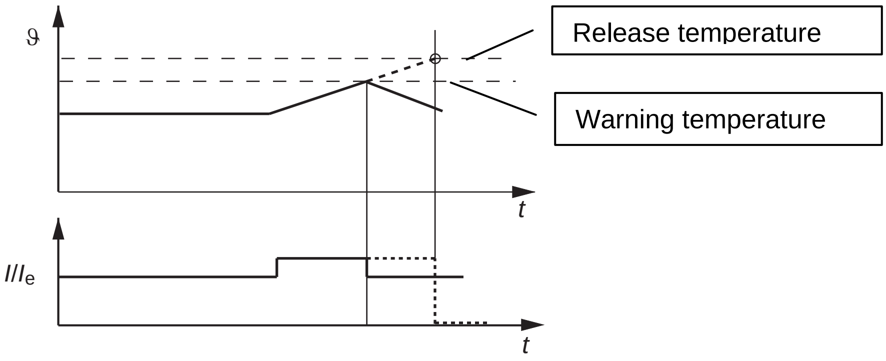


Fig. 4.1-16
Prewarning enables a disturbance to be rectified before a protective shutdown is required

The possibilities are manyfold and extend the function of the protective device to an integrated component for an optimum process control. Integration in the communication network of the control systems supports integration and the minimization of costs.

4.1.3 Protection against high overcurrents, short-circuit protection

See also Section **2.3.4**.

4.1.3.1 Definition and characteristic of a short-circuit

In accordance with IEC 60947-1, a short-circuit is a conductive path between two or more conductive parts forcing the electric potential differences between these conductive parts to be equal to or close to zero. In this section, a short-circuit is understood as a connection with very low impedance between a pole conductor and a second pole conductor, the neutral or the protective earth conductor or ground bypassing the load impedance and leading to the development of a very high overcurrent (> overload current of the circuit).

The characteristic and magnitude of the short-circuit current in a circuit are determined by the impedances of the components in the circuit. These are:

- Impedance of the power supply (transformer, connecting lines)
- Impedances of connecting points, any components (for example fuses, disconnect switches, circuit breakers) and lines in the circuit
- Impedance of the location of fault (frequently electric arc)

The magnitude of the prospective short-circuit current (symmetrical component) is a function of the driving voltage and the impedances of the short-circuit loop. For the purpose of estimation it is useful to determine the short-circuit current of the supplying transformer and the damping of the short-circuit current by the lines up to the fault location. For the short-circuit current of the transformer with a short-circuit directly at the terminals the following applies approximately:

$I_{\mathrm{ccT2}} = I_{\mathrm{2e}} \cdot 1/u_{\mathrm{k}} = (P_{\mathrm{T}}/(U_{\mathrm{2e}} \cdot \sqrt{3})) \cdot 1/u_{\mathrm{k}}$

I_{ccT2} Prospective short-circuit current on secondary (r.m.s. value)
I_{2e} Rated secondary current
u_{k} Short-circuit voltage
P_{T} Rated power of the transformer
U_{2e} Rated secondary voltage (pole-pole)

For an estimate of the damping effect of lines on the short-circuit current see RALVET [13].

If large motors are running on a supply, then their contribution to the entire short-circuit current should be taken into account. Their locked-rotor current can approximately serve for this.

Because of the lack of a load impedance in the short-circuit loop, short-circuit currents are strongly inductive. This has an effect on the peak value of the prospective short-circuit current, as depending on the time of occurrence of a short-circuit within a supply half cycle, a more or less high overshoot (prospective peak short-circuit current) is produced (**Fig. 4.1-17**).

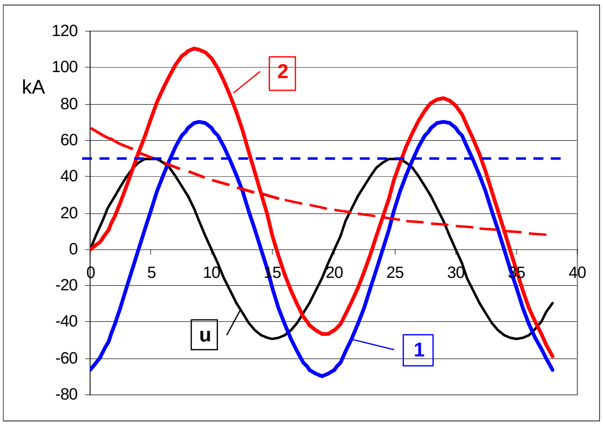


Fig. 4.1-17
Depending on the time of occurrence of a short-circuit and because of the high inductance of the short-circuit loop, an overshoot and a high initial current peak are produced.
1 Symmetrical short-circuit current (as an example 50 kA_{eff})
2 Characteristic of the current when switching on at voltage – zero crossover (most adverse point in time)
u Driving voltage

This overshoot is taken into account in the regulations by the factor *n* that should be taken into account when designing switchgear assemblies with respect to the short-circuit withstand capacity of the installation and of short-circuit switchgear with respect to its making capacity. The factor *n* is depending on the power of the power supply system and therefore on the prospective short-circuit current (**Tab. 4.1-6**).

r.m.s. value of the prospective short-circuit current [kA]	**Power factor** ***cos φ***	**Factor *n***
I ≥ 5	0.7	1.5
5 < *I* ≥ 10	0.5	1.7
10 < *I* ≥ 20	0.3	2.0
20 < *I* ≥ 50	0.25	2.1
50 < *I*	0.2	2.2

Tab. 4.1-6
Standard values for the factor ***n*** *in accordance with IEC 60439-1 for determining the electrodynamic short-circuit withstand capacity of switchgear assemblies. The r.m.s. value of the prospective short-circuit current should be multiplied by the factor* ***n*** *in order to determine the peak value of the prospective short-circuit current.*

4.1.3.2 Effects of and dangers in case of short-circuits

The high currents during short-circuits stress the components in the shorted circuit by high dynamic forces and strong heat generation in the current-carrying parts.

The forces developed are proportional to the square of the current flowing. Therefore the peak value of the short-circuit current is highly significant. The heat generation, too, is proportional to the square of the current.

Usually an electric arc is developing at the location of the short-circuit that can result in serious injuries to persons through burns, blinding or electric shock as well as it can lead to the damage or destruction of installation components.

4.1.3.3 Protection requirements

4.1.3.3.1 Switching capacity

The most important requirement for a short-circuit-protective device is sufficient switching capacity so that it is able to reliably manage the fault current. The project engineers and users have to ensure that the switching capacity I_{cu} or I_{cc} of the short-circuit protective devices or device combinations (for example circuit breaker plus contactor) at the given operating voltage is equal to or larger than the prospective short-circuit current occurring at the site of installation. The reference quantity for rating is thereby the symmetrical value. While with fuses it is naturally a question of the breaking capacity only, circuit breakers must also have a corresponding making capacity, as they also may make a circuit in which a short-circuit is present. This is ensured by means of test sequences.

With circuit breakers a distinction is made between the ultimate short-circuit switching capacity and the service short-circuit switching capacity that relates to reusability after a short-circuit. See Section **4.2.2.3.3**.

4.1.3.3.2 Current limitation

Due to the potential dangers of short-circuits it is desirable that they are quickly detected and to break them already in the first phase of current rise as far as possible (**Fig. 4.1-18**). This is intended to reduce the destructive energy to a minimum and to keep the extent of damage low. The smaller the damage due to a short-circuit, the lower will be the repair costs, the operational interruption and the resulting production losses. Modern circuit breakers and fuses have strongly current limiting properties.

IEC 60439 (low-voltage switchgear assemblies) takes these factors into account by dispensing from the requirement of verification of the short-circuit withstand capacity, if the symmetrical short-circuit current is ≤ 10 kA or the cut-off current I_D ≤ 17 kA.

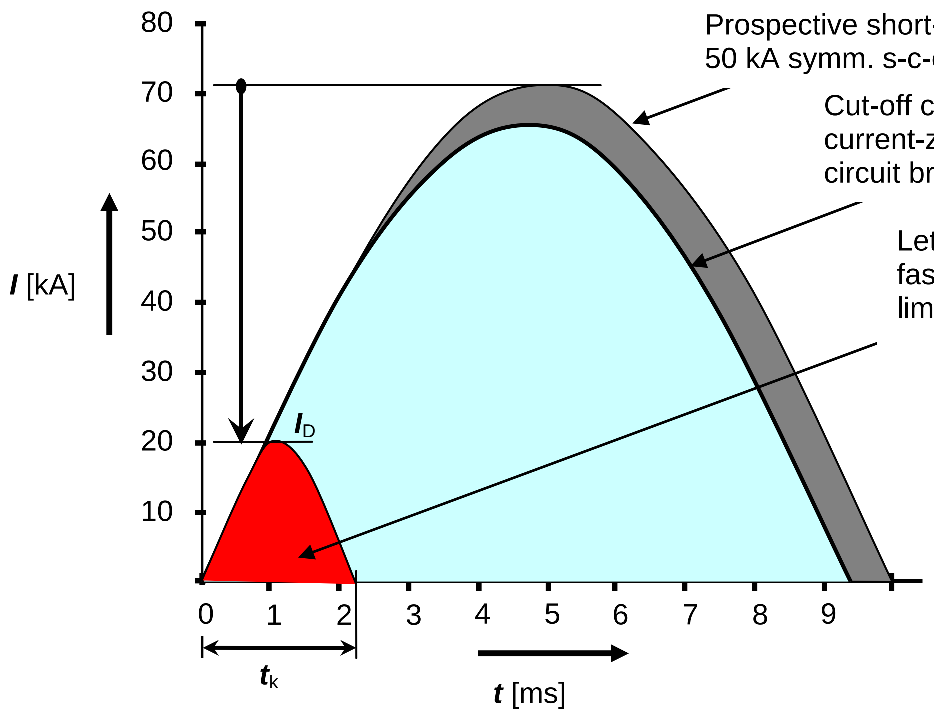


Fig. 4.1-18
Current limiting circuit breakers or fuses reduce the fault current and hence the mechanical and thermal stresses in the event of a fault
I_D Cut-off current
t_k Total breaking time

4.1.3.3.3 Selectivity

From the point of view of the operational safety and reliability of an entire low-voltage installation, it is usually desirable to specifically isolate the part of a system affected by a short-circuit in order to prevent spreading of the fault. Selectivity is intended to ensure that the protective shutdown is as close as possible to the location of the fault so that unaffected installation components can continue to operate normally. This is often also desired for safety reasons and in IEC 60439-1 (low-voltage switchgear assemblies) addressed for installations that require a high level of continuity in current supply.

In buildings and industrial plants, radial distribution networks are the norm. In radial distribution systems there are several protective devices in series, usually with decreasing rated currents from the supply end to the load end. While the operational currents decrease from the supply end to the load end, in the event of a short-circuit the same fault current will flow through all the protective devices connected in series. By a cascading of the trip characteristics it must be ensured that only the respective protective device that is closest to the location of the fault is activated and hence the fault is selectively limited to the smallest possible part of the installation.

The basic prerequisite for selectivity of protective devices connected in series is that the trip characteristic of the downstream (closer to the load) protective device is faster than that of the upstream device. And all this taking into account all tolerances and over the entire current range up to largest prospective short-circuit current.

Special attention should be paid to the area of high overcurrents, where the effects of current limitation and breaking times are significant. Thus an upstream fuse does not operate if the entire I^2t of the downstream protective device (fuse, circuit breaker) is smaller than the melting I^2t the fuse. An upstream circuit breaker on the other hand does not operate if the maximum cut-off current I_D of the downstream protective device is smaller than the activation value of its magnetic release.

In individual cases, reference to manufacture documents and frequently the technical support of the manufacturer is required for the correct selection of devices. The basic facts are presented below.

Selectivity between fuses connected in series

Fuses connected in series act selectively if their time current-characteristic curves have sufficient mutual spacing and their tolerance bands do not touch (**Fig. 4.1-19**).

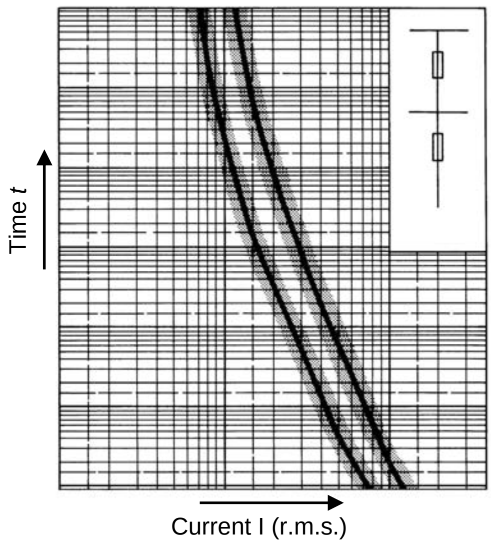


Fig. 4.1-19
Selectivity between fuses connected in series

At high short-circuit currents the melting $I^2 \cdot t$ value of the upstream fuse must be larger than the breaking $I^2 \cdot t$ value (melting and clearing time) of the smaller downstream fuse. This is usually the case if their rated currents differ by a factor of 1.6 or more.

Selectivity of circuit breakers connected in series

Current selectivity

In distribution networks, the rated currents of the switches decrease constantly from the transformer to the load. As the short-circuit releases normally operate at a multiple of the rated current, their release levels decrease in the same way with distance from the supply. As the prospective short-circuit currents also become smaller with increasing distance from the supply point due to line damping, a so-called natural selectivity can be created via the current magnitude. This means that the maximum short-circuit current with a short-circuit on the load-side of the switch 2 (**Fig. 4.1-20**) is below the trip value of the magnetic release of switch 1. The short-circuit currents must be known at the installation sites of the switches.

Selectivity is usually not assured with short-circuit currents above the response value of the magnetic release of the upstream circuit breaker.

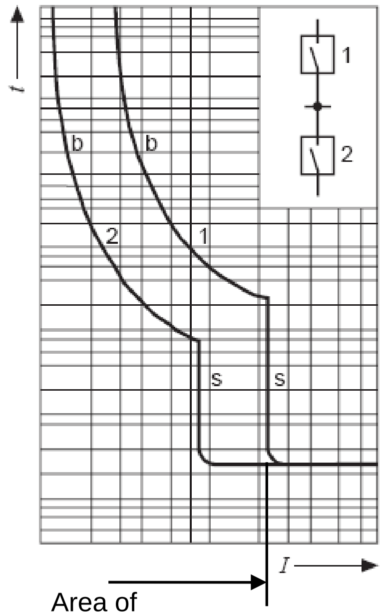


Fig. 4.1-20
Current selectivity of two circuit breakers in series is given, if the prospective short-circuit current downstream of Circuit breaker 2 is smaller than the trip value of the magnetic release of Switch 1
b = Overload release
s = Short-circuit release

When assessing the current selectivity the tolerance of the short-circuit trigger (+/-20 % in accordance with IEC 60947-2) should be taken into account.

Time selectivity

If current selectivity between circuit breakers is not possible, selectivity must be achieved by cascading of the trip times, i.e. the upstream circuit breaker operates with a short delay to give the downstream circuit breaker time to clear the short-circuit. If the short-circuit occurs between the two switches, then it will continue during the short trip delay time of the switch 1 and after lapse of this time it will be switched off by the latter (**Fig. 4.1-21**).

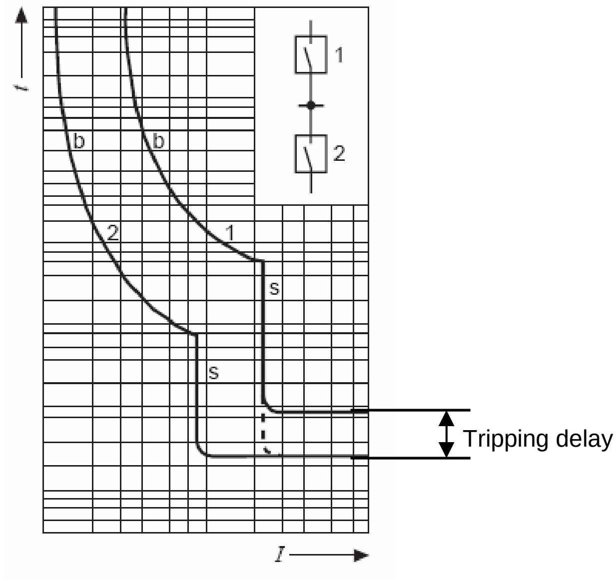


Fig. 4.1-21
Time selectivity of two circuit breakers in series
b = Overload release
s = Short-circuit release (switch 1 with short-time delay; utilization category B)

The cascading of trip times requires that Switch 1 is capable of carrying the short-circuit current during the trip delay time. This is the case when using circuit breakers of utilization category B. The critical variable is the rated short-time current I_{cw} that determines the magnitude of the permissible short-time current during a defined period. It is usually stated as the 1s-current and can be converted for other times with I^2t = const. (see also Section **2.3.4.3**).

Selectivity between fuse and downstream circuit breaker

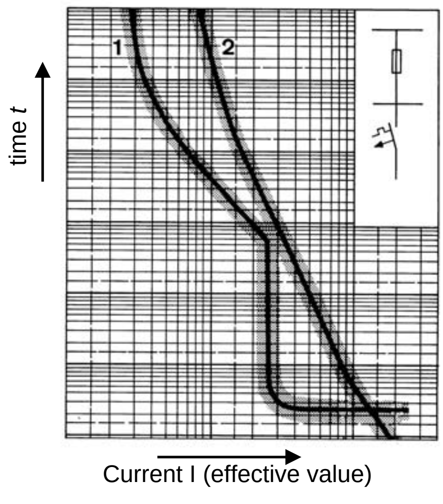


Fig. 4.1-22
Selectivity between fuse and downstream circuit breaker
1 = Circuit breaker
2 = Fuse

In the overload range selectivity is given, if the trip characteristic of the overload release lies under the characteristic curve of the fuse (considering the tolerance band). In the short-circuit range selectivity is given to the extent that the total breaking time (incl. clearing time) of the circuit breaker is below the melting characteristic of the fuse.

Selectivity between a circuit breaker and downstream fuse

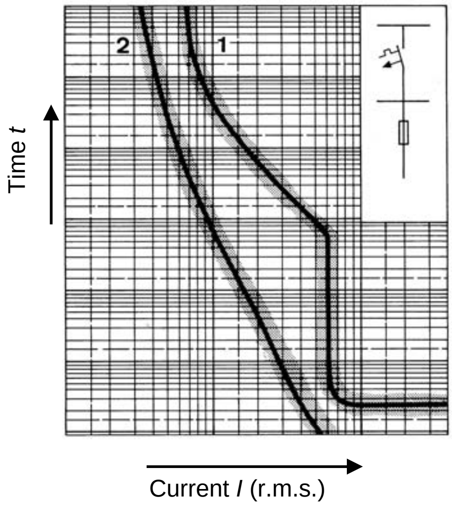


Fig. 4.1-23
Selectivity between circuit breaker and downstream fuse
1 = Circuit breaker
2 = Fuse

Selectivity in the tripping range of the short-circuit release of the circuit breaker is given when the cut-off current of the fuse is smaller than its trip value.

Selectivity and undervoltage

In a short-circuit the supply voltage breaks down at the short-circuit location. The size of the residual voltage depends on the impedance of the fault. If an electric arc is produced, the voltage is appr. 30 V to 70 V.

As the short-circuit current flows over the entire power line up to power source, along this line there is a voltage drop whose size is determined by the impedances lying between the two points. All connected electrical consumers are affected by the voltage drop and the closer they are to the fault location the greater is this effect. Devices such as contactors or undervoltage releases of circuit breakers may trip depending on the amount and duration of the voltage drop.

In order to guarantee operational continuity, suitable off-delays or remaking equipment should be provided. When short-circuits are broken by current limiting circuit breakers, voltage breakdowns are so short that no disruptions should be expected.

4.1.3.3.4 Short-circuit coordination

Short-circuit coordination determines the extent of damage and consequences with respect to the operational interruption as a consequence of a short-circuit for motor starters and load feeders.

See Section **2.3.4.5.2**.

4.2 Protective devices

4.2.1 Fuses

Fuses as the oldest protective devices in electrical engineering still have a wide area of application, although circuit breakers are continually gaining currency in plant construction and are supplanting fuses.

4.2.1.1 Principle of operation

Protection by fuses is based on letting a piece of electrical conductor melt or fuse, providing so to speak an intentional weak point in a circuit. To this end, a certain current-generated temperature is required. Full-range fuses have a soldered joint that is the intended weakpoint and bottleneck of the conductor for small overcurrents and a constricted area of the conductor that is broken by high overcurrents (short-circuit currents) by the Joulean heat impulse I^2t. Part-range fuses are exclusively designed for short-circuit protection.

4.2.1.1.1 Current limitation

Cut-off current (let-through current)

Fuses trip at very high currents so quickly that the circuit is broken before the short-circuit current can reach its prospective peak value. The highest instantaneous value of the current that is attained during the circuit breaking process is known as the cut-off (let-through) current I_D. The current limitation is specified by means of cut-off current diagrams (**Fig. 4.2-1**). These state the peak value of the current that may flow through the fuse as a function of the prospective short-circuit current.

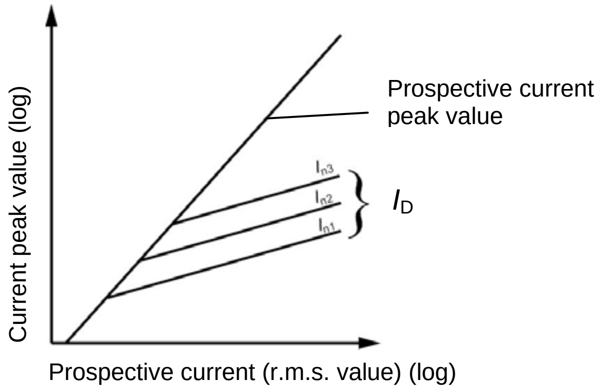


Fig. 4.2-1
Cut-off current diagram for fuses
I_{n1}, I_{n2}, I_{n3} = rated currents of fuses
I_D = max. cut-off current

Let-through - $I^2 \cdot t$ value

The $I^2 \cdot t$ value (correct $\int i^2 \cdot dt$) represents the heat energy that the fuse lets through and that stresses the circuit up to the location of the fault. The better the current limitation, the more the fault current is reduced and the smaller is the destructive effect of a short-circuit. The faster the short-circuit is cleared, the smaller is the $I^2 \cdot t$ value.

Distinction is made between the melting $I^2 \cdot t$, which occurs up to melting of the fuse-conductor, and the total $I^2 \cdot t$ value which represents the total energy until quenching of the electric arc of the fuse. The two values only start to diverge significantly with large short-circuit currents or when the total breaking times are shorter than a half-cycle. The $I^2 \cdot t$–values of the fuses are critical for the mutual selectivity of fuses at high currents.

4.2.1.1.2 Breaking capacity

The effective current limitation and the associated very high breaking capacity are specific properties of fuses that assure their continued use in certain applications in short-circuit protection.

4.2.1.2 Standards and utilization categories

So that fuses can be adapted to the respective requirements, a variety of models with various current-time characteristic curves have been developed. The parameters and tests are defined in various standards. The applicable standards for low-voltage fuses are

IEC 60269 – 1 (General requirements)

IEC 60269 – 2 (Fuses intended for use by authorized persons)

IEC 60269 – 3 (Fuses intended for use by unskilled persons)

IEC 60269 – 4 (Fuses intended for the protection of semiconductor devices).

4.2.1.2.1 Classification and time/current zones

The area of application is designated by two letters, the first of which specifies the breaking current range and the second the utilization category. A summary of the classification of low-voltage fuses is provided by **Tab. 4.2-1**.

Breaking range	Continuous load up to	Utilization category	Characteristic, Protection of
"g" [1]	I_n	"gG" „gL"	Conductors, Cables, Devices
		"gM"	Switchgear in motor circuits
		"gR"," gS" [3]	Semiconductors
		"gD"	Fuses with time-delay
		"gN"	Fuses without time-delay
"a" [2]	I_n	"aM"	Switchgear in motor circuits
		"aR"	Semiconductors

[1] Full-range fuses, [2] Partial range fuses, [3] Type "R" is faster than Type "S"

Tab. 4.2-1
Classification of low-voltage fuses according to breaking current range and utilization category
IEC 60269-1 ed. 4.0. Copyright © IEC, Geneva, Switzerland. www.iec.ch.

The letter "g" indicates full-range fuses that can continuously conduct currents at least up to their rated current I_n and that can break currents from the smallest melting current up to the rated breaking current. These include for example "gG" fuses for general applications (cable, conductor and device protection).

The letter "a" signifies partial range fuses that can continuously conduct currents at least up to their rated current I_n and that can break currents above of a certain multiple of their rated current up to the rated breaking current. This functional class includes for example the "aM" fuses for protection of motor circuits, whose breaking range begins at over four times the rated current and which hence are solely designed for short-circuit protection.

Depending on the application requirements, various time/current zones are specified. In **Fig. 4.2-2** the principal characteristics of time/current zones for the utilization categories "g" and "a" are presented. The area of the overload curve of fuses of Class "aM" must be protected by an overload protective device. The release curve of the protective device must be below the overload curve of the "aM" fuse.

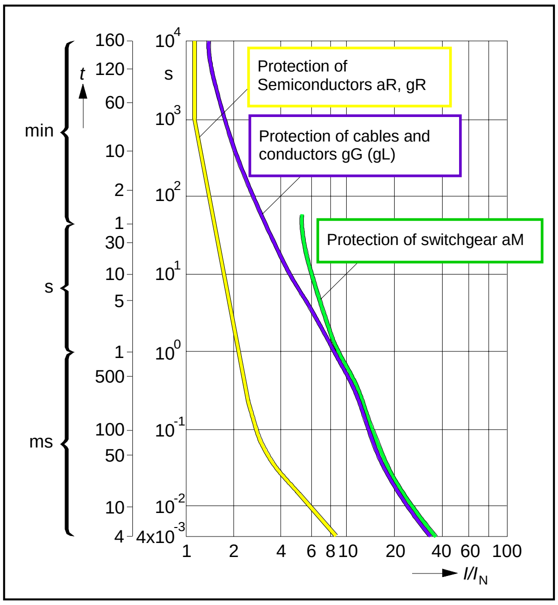


Fig. 4.2-2
Principal characteristics of the time/current zones of fuses

Usually the manufacturers of fuses state these characteristic curves as mean values of a tolerance band.

Selectivity

The time/current ranges are coordinated for “gG”/“gL” fuses so that fuses whose rated currents are in the ratio 1:1.6 are usually mutually selective. See also Section **4.1.3.3.3** on selectivity.

4.2.1.3 Designs

The design of fuses has developed over time. A distinction is made between designs that are mainly intended for use by unskilled persons (for example screw-type fuses) and those that are intended for operation by authorized persons (for example fuses with blade contacts).

Screw-type fuses (for example D System)
The D System is characterized by the non-interchangeability of fuse-links with respect to the rated current and by their touch protection. They are suitable for industrial applications as well as for domestic installation and can be operated by unskilled persons. Screw-type fuses are not suitable for switching operational currents (i.e. they must be screwed in and out without load current flowing).

Fuses with blade contacts (for example the HRC System)
The HRC system (low-voltage/high rupturing capacity fuse system) is a standardized fuse system, that consists of a fuse base, a replaceable fuse-link and an operator element for replacing the fuse-link. HRC fuses can also be equipped with a trip-indicator and tripping devices.

Non-interchangeability with respect to the rated current and touch protection are not provided; the HRC system is therefore not suitable for operation by unskilled persons.

Although fuse bases are equipped with phase partition walls and side walls, they are not touch-safe for fuse replacement. This should therefore only be performed with special protective equipment. The design sizes of the system have to be indicated with their maximum current ratings. Within a current range specified by the design size, the use of any fuse rated current is possible.

Fuse-switch-disconnectors

Safe changing of fuse-links of the HRC system can be achieved by the use of fuse-switch-disconnectors. The fuse-links are snapped into a cover that covers the entire base and are pulled out of the contacts with this cover for replacement. This means that the circuit can be made and broken under load.

A further development of the above is the “switch-disconnector-fuse” combination. To make the replacement of fuse-links even safer, they are first isolated from the voltage on both sides. This means that neither return voltages nor the direction of power supply have to be taken into account by the user. For reasons of space economy, in most cases busbar designs are used.

4.2.2 Circuit breakers

4.2.2.1 Principle of operation and design

The circuit breaker is a mechanical switching device, capable of making, carrying and breaking currents under normal circuit conditions and also making, carrying for a specified time and breaking currents under specified abnormal conditions such as those of short-circuit (IEC 60947-1).

Circuit breakers have the capacity to break short-circuits. They are classified according to their breaking capacity, their design and their capability to limit short-circuit currents. They are classified according to the following groups:

- ***Circuit breakers that clear at current zero***
- ***Current-limiting circuit breakers***

The devices of both groups can be further subdivided according to design:

- ***Miniature Circuit Breakers (MCB)***
  Single pole or modular multipole circuit breakers for up to around 100 A rated current for line protection with or without residual current release for installation applications
- ***Moulded Case Circuit Breakers*** *(**MCCB**)*
  Circuit breakers with a housing of insulating material that forms an integral part of the circuit breaker (rated currents typically up to around 1600 A)
- ***Air Circuit Breakers*** *(**ACB**)*
  Large installation switches with open design (rated currents typically 300 … > 3000 A)

4.2.2.2 Standards, functions and utilization categories

4.2.2.2.1 Standards

The standards that are applicable for circuit breakers are

- IEC 60947 – 1 (Low-voltage Switchgear, General Requirements) and
- IEC 60947 – 2 (Circuit Breakers).

For use in North America, the standards and approvals under UL 489 or CSA 22.2 apply. Devices that are not approved under these standards are not recognized or approved as circuit breakers in North America.

For circuit breakers with motor protection function IEC 60947-4-1 also applies. Such circuit breakers can be used in North America under UL 508 under certain conditions (construction type E). For details with respect to applications in North America, see UL-WP001A-EN-P [15].

4.2.2.2.2 Functions and utilization categories

A circuit breaker basically consists of an actuation device (manual or – optionally – remote controlled), usually an (thermal or electronic) overcurrent release, an electromagnetic short-circuit release, a tripping mechanism with spring storage (switch latch), the main contact system and optional auxiliary contacts. The combination of these functions in one unit means that installations can be made compact and that circuit breakers can be integrated in the automation environment. Thus modern starter combinations consist of only two components – a circuit breaker with motor protection characteristic and a contactor.

Circuit breakers offer functions such as:

- Short-circuit protection
- Line, load (motor), plant protection

- Signaling of the operational state
- Signaling of tripping
- Operational switching
- Remote control
- Disconnection
- Locking functions by means of a padlock

Depending on design, they can be used not only as short-circuit protection devices but also as motor protection circuit breakers, load switches, main switches or disconnectors.

With respect to selectivity between short-circuit protective equipment, IEC 60947-2 distinguishes between two utilization categories (*Copyright © IEC, Geneva, Switzerland, www.iec.ch*).

- **Utilization category A** → Circuit breakers without tripping delay
  IEC-Definition: Circuit-breakers not specifically intended for selectivity under short-circuit conditions with respect to other short-circuit protective devices in series on the load side, i.e. without an intentional short-time delay provided for selectivity under short-circuit conditions, and therefore without a short-time withstand current rating according to 4.3.5.4. [1)]
- **Utilization category B** → Circuit breakers with short-time delay
  IEC-Definition: Circuit-breakers specifically intended for selectivity under short-circuit conditions with respect to other short-circuit protective devices in series on the load side, i.e. with an intentional short-time delay (which may be adjustable), provided for selectivity under short-circuit conditions. Such circuit breakers have a short-time withstand rating according to 4.3.5.4. [1)]

[1)] *Rated short-time withstand current (I_{CW}): At a.c. this is the r.m.s. value of the a.c.-component of the prospective short-circuit current during the time of short-time delay.*

The large majority of circuit breakers is used at the load-end of circuits and corresponds to utilization category A.

Circuit breakers with motor protection characteristic also comply with the utilization categories for switching loads, for example AC-3 under IEC 60947-4-1.

4.2.2.3 Design of a circuit breaker

The parts of the circuit breaker detailed in **Fig. 4.2-3** are precisely coordinated so that the common tasks, the rapid disconnection of short-circuit currents and the dependable recognition of overloads, can be performed optimally.

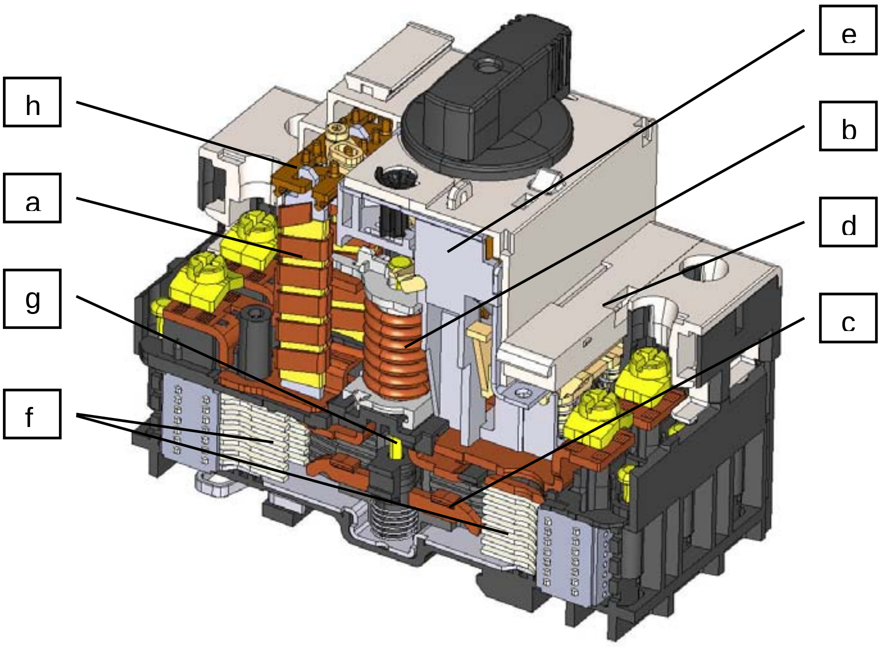


Fig. 4.2-3
The main functional elements of a circuit breaker for motor protection
a) Thermal overcurrent release
b) Electromagnetic overcurrent release
c) Main contact system
d) Auxiliary switch position
e) Switch latch
f) Arcing chamber (de-ion plates)
g) Plunger armature
h) Differential trip slide

In larger circuit breakers (> approx. 100 A), electronic trip and communication modules are increasingly being used. These offer a high degree of flexibility with respect to the selection of application-specific parameters and support the integration of devices in superordinated control and management systems.

4.2.2.3.1 Thermal overcurrent releases

The thermal overcurrent releases of circuit breakers act in the same way as those of thermal motor protection relays (bimetal overload relays) and are subject to the same standards if they are used for motor protection. See also Section **4.2.4.1**. Tripping is normally effected via the switch latch of the circuit breakers and results in the opening of the main contacts. Resetting is by manual or remote actuation of the switch after the bimetals have cooled below the reset threshold.

In the case of circuit breakers with thermally delayed overload releases and low setting currents (ca. < 20 A), the resistance of the circuit with the heating windings of the bimetal strips and the coil of the undelayed electromagnetic short-circuit triggers is comparatively large. It may be so large that it damps any size of (prospective) short-circuit current to a value that the switch can still cope with thermally and dynamically and can hence also disconnect. Such circuit breakers are intrinsically safe against short-circuits.

4.2.2.3.2 Electromagnetic overcurrent releases

In circuit breakers with motor protection characteristic overcurrents from a value of 10 ... 16 times the upper scale setting immediately cause the electromagnetic overcurrent release to act. High efficiency motors may require higher magnetic trip levels (see **1.7.1.2.1**). The precise tripping value is either adjustable (matching for selectivity or various making current peaks in case of transformer and generator protection) or is determined by the design. In circuit breakers for plant and line protection the tripping zone is lower.

In small circuit breakers (usually < 100 A), the pole conductor is shaped in the form of a small coil. If a high overcurrent flows through these coils, a force acts on the armature enclosed by the coil. This armature unlocks the loaded switch latch that releases the stored spring energy and hence opens the main contacts and disconnects the overcurrent.

Plunger for high current-limiting circuit breakers

Current-limiting circuit breakers limit the fault current and hence reduce the mechanical and thermal stress in the event of a fault (see Section **4.1.3.3.2**). Circuit breakers with rated currents up to around 100 A are offered for the rapid disconnection of the short-circuit current with a plunger system, that in the event of a short-circuit additionally forces the main contacts open and hence supports extremely short break times (**Fig. 4.2-4**).

An alternative to the plunger system at larger rated currents is the slot motor that opens the contacts very fast, largely by means of electrodynamic forces.

The faster it breaks, the less energy has to be managed in the switch and the more compact the circuit breaker can be. This means that this is prerequisite for circuit breakers to be built with compact external dimensions.

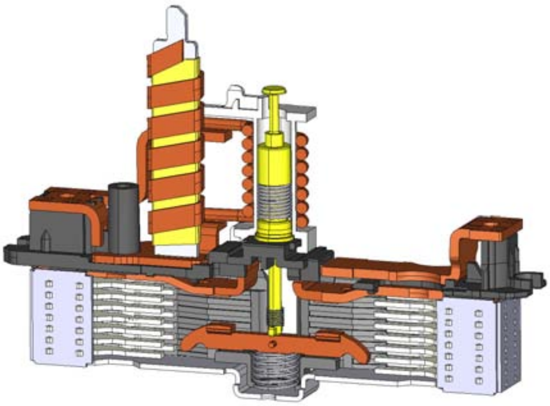


Fig. 4.2-4
The contacts of a high current-limiting circuit breaker are forced open in the event of a short-circuit by a plunger and the current is directed immediately to the arcing chambers. The circuit is such broken even while the current is still rising.

4.2.2.3.3 Main contact system and switching capacity

The requirements on a circuit breaker main contact are a high making capacity, high breaking capacity, low heat dissipation at operational current, low contact erosion, small inertia and optimum shape for a favorable movement of the electric arc. The switching arc should quickly be directed out from the area between the contact surfaces, cooled, divided, extended and thus extinguished. The de-ion plates must form a functional unit with the main contact with respect to shape and arrangement.

In order to optimally fulfill these high requirements, the very highest demands are placed on the design and materials and not least on the simulation and testing techniques.

Contact systems are designed to produce optimum switching performance at the main rated voltage. The number of de-ion plates is critical for the electric arc voltage during circuit breaking and hence for the switching capacity and current limitation. For example a contact system designed for 400 V has a reduced switching capacity at supply voltages above 400 V (supply voltages below 400 V are thereby uncritical). Use at for example 690 V may therefore only be possible with reduced switching capacity. The performance data for the specified operational voltage should be respected.

Circuit breakers must be capable to control the largest possible short-circuit current at the point of installation at the given operational voltage. Intrinsically short-circuit proof circuit breakers (Section **4.2.2.4.1**) can be used in supplies of any magnitude of short-circuit current, as their internal impedance limits the short-circuit current to the switching capacity of the switch (or below). If the switching capacity of the circuit breaker is smaller than required, then a backup protection must be provided (fuse or circuit breaker connected in series). The required switching capacity must be ensured in conjunction with the backup protection device. The sizing of the backup protection can be obtained from the product documentation.

Ultimate switching capacity and service switching capacity

IEC 60947-2 makes distinction between the rated ultimate short-circuit breaking capacity I_{CU} and the rated service short-circuit breaking capacity I_{CS}:

- **Rated ultimate short-circuit breaking capacity I_{CU}**
  The test sequence is O-t-CO
  Circuit breakers that have operated at the level of the ultimate short-circuit breaking capacity are only limited serviceable afterward. There may be changes in the overload tripping characteristic and increased temperature rises as a consequence of erosion of contact material.
- **Rated service short-circuit breaking capacity I_{CS}**
  The test sequence is O-t-CO-t-CO
  Circuit breakers that have operated at the level of the service short-circuit breaking capacity are further serviceable afterward.

O breaking the short-circuit from the closed state
t time interval
CO switching onto the short-circuit followed by breaking it

The ratings of circuit breakers for I_{CU} are usually higher than for I_{CS}. The majority of circuit breakers is therefore (for cost reasons) selected according to I_{CU}. In plants in which down-time must be kept as short as possible, product selection should be based on I_{CS}.

After a short-circuit has been broken, it is generally recommended to examine the device to make sure it is fully functional.

Let-through values

The essential quality attributes with respect to good short-circuit protection are the let-through values (**Fig. 4.2-5**). The magnitude of the cut-off current and let-through energy in relation to the prospective short-circuit current I_{cp} provide information about the quality of current limitation by the switch. They show the extent to which downstream devices such as contactors or switches are stressed in the event of a short-circuit. The let-through values directly affect the sizing of these series-connected devices – for example short-circuit coordination type 2 without oversized contactors – and determine the constructional design of the installation.

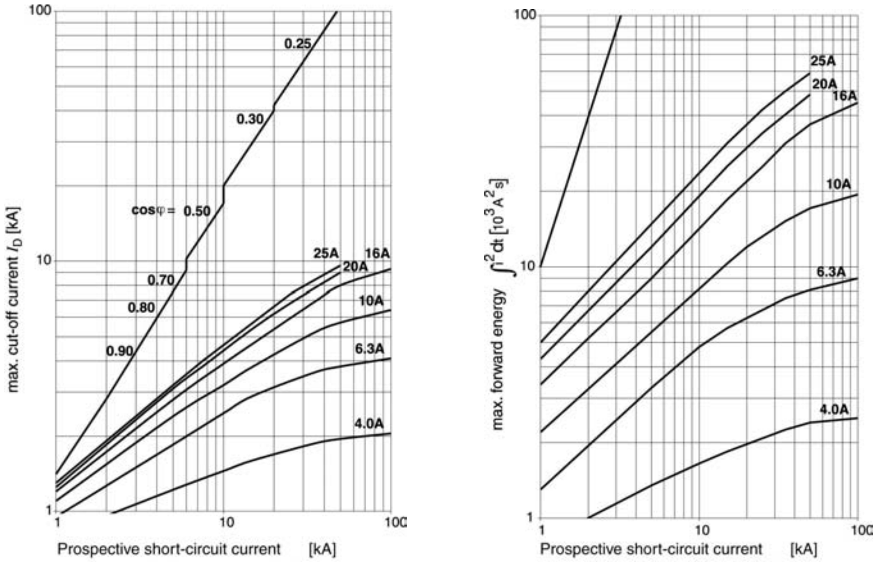


Fig. 4.2-5
Max. cut-off current and max. forward (let-through) energy of strongly current limiting circuit breakers at a rated operational voltage of 415 V

Life span of circuit breakers

IEC 60947-2 defines the number of switching operations that a circuit breaker has to perform without load, at normal load, at overload or with a short-circuit. The values vary between two breaks (O-t-CO) for the rated ultimate short-circuit breaking capacity and a couple of thousand operations for purely mechanical switching without load.

The electrical life span (contact life span) of a circuit breaker like with contactors depends on the size of the current to be broken. Small currents in the order of the rated current or the tripping range of thermally delayed overload releases have a much smaller effect on the contact life than short-circuit currents of the magnitude of the breaking capacity. The contacts may be so eroded even after exposure to just a few high short-circuit currents that replacement of the circuit breaker is required. The short-circuit currents that arise in practice are usually well below the calculated maximum values and the switching capacity of the switches deployed. They therefore cause less contact erosion.

Operational switching

In the lower power range, circuit breakers are also used to manually operate smaller – frequently mobile – equipment and devices (for example milling machines, circular saws, submersible pumps). The electrical life of the switches is rarely used to the full at the low number of operations typical in these applications. The circuit breakers with motor protection characteristic replace the combination fuse, motor protective device and load switch.

Auxiliary contacts and displays

Auxiliary contacts enable the functional integration of the protective device in the control system. ON, OFF, overload and/or short-circuit tripping can be signaled with the aid of the appropriate auxiliary contacts. These auxiliary switches can be mounted on or inserted in the circuit breaker and are either connected to terminals or connectable via loose wire ends.

In addition to auxiliary switches, circuit breakers are often equipped with visual indicators of the state of operation and also often for the tripped state and the cause of tripping. These are valuable aids for diagnosis on site during commissioning and fault rectification.

Shunt-trip and undervoltage releases

Shunt-trip releases enable remote circuit breaking by means of a control signal, for example for electrical interlocking.

The undervoltage release switches the circuit breaker OFF when the voltage falls below a (usually fix) certain level of the applied voltage and is used for example for detecting voltage outages. They are in particular used as safety components, for example to prevent automatic restarts after a voltage outage, for interlocking circuits, for EMERGENCY STOP functions and for remote release.

Motor operators

Motor or remote operator units open the possibility to issue all commands to circuit breakers remotely. The functions that are usually manually performed can thus be actuated from remote. The load feeders can thus be switched-on and -off without direct intervention of an operator on site. Resetting of a circuit breaker that has tripped is thus possible in remote-controlled distribution stations.

4.2.2.4 Application of circuit breakers

Depending on their design and accessories, circuit breakers can perform the following switchgear functions:

- Circuit breaker
- Motor protection circuit breaker (manual motor starter)
- Load switch
- Disconnector
- Main switch
- EMERGENCY STOP switch

The specific properties of the respective design should be taken into account to ensure that the best suitable circuit breakers are selected for the respective applications. See also Section **2.2.1**.

4.2.2.4.1 Application as circuit breaker

Current-zero quenching circuit breakers

Current-zero quenching circuit breakers have little current limitation and break the short-circuit close to the natural current zero crossover. Because of their high let-through values they are mainly used for protecting lines and installations. In versions according to utilization category B (with breaking delay) they are applied in selective power supply systems with time cascading.

Current-limiting circuit breakers

Current-limiting circuit breakers simplify the applications. They make complex supply-short-circuit current calculations for every single location of switch installation unnecessary and make short-circuit coordination nearly as simple as with conventional fuses.

Properties of circuit breakers to simplify planning work:

- High switching capacity renders supply calculations unnecessary:
  If the switching capacity of the circuit breaker is higher than the short-circuit level at the site of installation (with motor outputs typically 1 ... 20 kA) then there is no need to perform supply calculations.
- Low let-through values (cut-off current and $I^2 \cdot t$ value):
  Weld-free or only slightly welding starter combinations of circuit breakers and contactors are often possible without overrating the contactors and are therefore economical. The manufacturers conduct coordination tests and issue coordination tables in accordance with for example IEC 60947-4-1 coordination type “1” or “2”.
- The verification of the short-circuit withstand capacity in accordance with IEC 60439-1 (low-voltage switchgear assemblies) is not required with cut-off currents ≤ 17 kA.

Circuit breakers for the protection of motors

These are at least equipped with to the motor current adjustable releases (bimetal or electronic) with motor protection characteristic. Modern motor protection-circuit breakers are also featuring:

- Ambient temperature compensation (in case of bimetals)
- Safe single-phasing protection (for example special calibration, differential trip slider or electronic fault detection). This is also the prerequisite for use with motors of the ignition protection type “Increased Safety” (EEx e).

Standard circuit breakers – above all in the range of higher rated currents – normally only offer line protection and hence are not suitable for the overload protection of motors. For use in motor circuits, additional suitable motor protective devices should be provided. It should thereby be noted that the overload characteristic of the circuit breakers must be slower than those of the motor protective devices, so that at overload the motor protective device and not the circuit breaker trips (see IEC 60947-4-1 Annex B.4).

Fig. 4.2-6
Modern high current-limiting circuit breakers with motor protection characteristic

Circuit breakers with motor protection characteristic are used as so-called self-protected motor starters (combination motor starter). At smaller rated currents the motor protection circuit breakers often serve as manual motor starter and must then be verified under IEC 60947-4-1 as motor starters. Modern motor protection circuit breakers have in comparison with the conventional design of motor protection switches a high short-circuit switching capacity.

Circuit breakers for distribution systems and line protection

The requirements on circuit breakers for distribution systems and line protection are different compared to circuit breakers for motor protection:

- The current range is often fixed
- The thermal triggers are less accurate
- Usually there is no temperature compensation
- The tripping level of the electromagnetic short-circuit release is usually lower and often adjustable
- Switches of utilization category B have a (usually adjustable) time delay and a short-term current carrying capacity (I_{cw}) and are thus suitable for time-selective cascading

In circuit breakers with motor protection characteristic, line protection is also automatically assured as the lines are thermally less critical than motors. Depending on the respective national standard, the lines may be rated according to the current-setting on the circuit breaker or according to the upper end of the current scale. While with fuses of Type “gG” an overrating of the fuse and hence of the cross-section of the protected line by one or two current steps is necessary to prevent tripping during motor start-up, motor lines protected by circuit breakers can have smaller cross-sections and hence be more fully utilized.

Circuit breakers as load switches

See also Section **2.2.1.2**.

Circuit breakers fulfill the requirements on load switches and can be used as such.

Circuit breakers as disconnectors

See also Section **2.2.1.1**. Circuit breakers often fulfill the disconnector requirements and therefore can be used as such. Such circuit breakers with disconnector properties must be correspondingly tested and marked with the disconnector symbol.

Fig. 4.2-7
Switch symbol for circuit breakers with disconnector function. The horizontal line symbolizes the disconnector properties, the cross stands for the circuit breaker function.

Circuit breakers as main switches (supply disconnector devices)

See also Section **2.2.1.5**.

Under IEC 60204-1, circuit breakers are expressly authorized as main switches insofar as they possess disconnector properties.

Circuit breakers as EMERGENCY STOP switches

See also Section **2.2.1.6.**

According to IEC 60204-1, supply disconnect switches are permitted as EMERGENCY STOP devices if they are easily accessible for the operating personnel. For use as an EMERGENCY STOP switch the handle must be red on a yellow background.

4.2.2.5 Installation of circuit breakers, safety clearances

See also Section **2.3.9**.

Circuit breakers can cope with very high currents at high voltages when breaking short-circuits. During the breaking process, the contact systems and arcing chambers consequently convert large amounts of power into heat energy. In addition to high temperature rises of components such as contacts, de-ion plates and walls of the contact chambers, the energy converted into an arc results in heating of the air in the contact system to several thousand degrees Celsius and hence to the formation of a conductive plasma. This plasma is usually emitted through blow-out openings to the outside and must not reach any conductive parts to prevent secondary short-circuits.

For this season, safety clearances are specified for circuit breakers (**Fig. 4.2-8**), within which no conductive parts – for example metallic walls or uninsulated conductors – may be located. Frequently additional insulation components (phase partition walls or covers; in some cases optional) are used. With some products, additional insulation of the connected conductors is required in accordance with manufacturer specifications. Non-compliance with the safety clearances can result in accidents with most severe consequences.

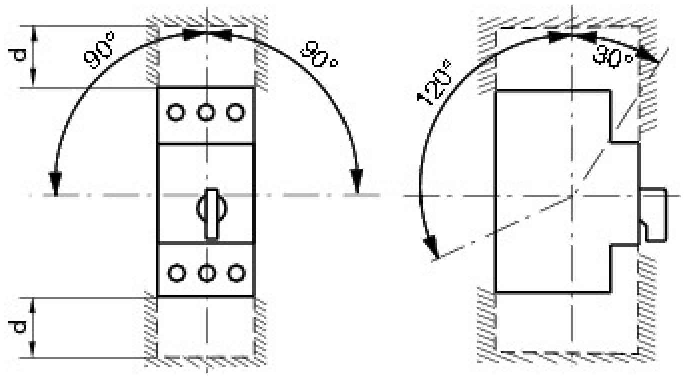


Fig. 4.2-8
It is essential that the safety clearances are observed. No conductive parts may be located within the hatched zones such as metallic walls or uninsulated conductors.

4.2.3 Miniature Circuit Breakers MCB

4.2.3.1 Principle of operation and design

Miniature circuit breakers are primarily designed to protect cables and lines against overload (thermal) and short-circuit (electromagnetic). They thus care for protecting this electrical equipment against excessive temperature rises and destruction in the event of a short-circuit. Miniature circuit breakers are used in distribution networks in homes and in industrial applications. They meet the requirements for different applications by various designs and with the aid of a comprehensive range of accessories (for example auxiliary and signal contacts etc.).

The structural shape of all line protection switches is similar. Certain dimensions are defined by the installation standards (in some cases national). The major differences lie in the widths (for example 12.5 and 17.5 mm) or depths (for example 68 and 92.5 mm). The breaking capacity is one of the factors that determine the size.

4.2.3.2 Standards, tripping characteristics and rated switching capacity

MCB's are subject to international and national norms. The design and test requirements are defined in the standard IEC 60898. For the various applications three trip characteristics B, C and D are defined in IEC 60898 (**Fig. 4.2-9**):

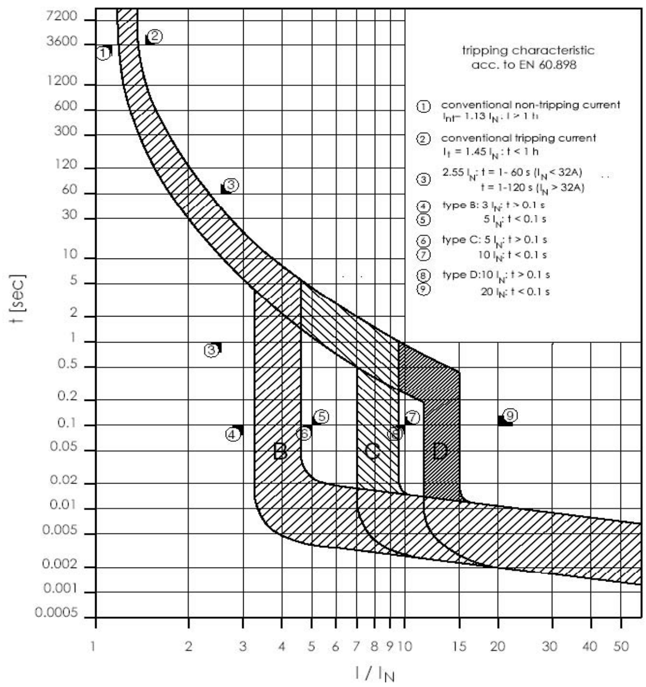


Fig. 4.2-9
The tripping characteristics B, C and D under IEC 60898 are distinguished by the trip level of the short-circuit trigger

- *Trip characteristic **B** is the standard characteristic for wall outlet circuits in domestic and utility buildings (I> ≥3 … 5*I_e)*
- *Trip characteristic **C** is advantageous when using electrical equipment with higher inrush currents as for example of lamps and motors (I> ≥5 … 10*I_e)*
- *Trip characteristic **D** is adapted to electrical equipment that can produce strong current surges such as transformers, electromagnetic valves or capacitors (I> ≥10 … 20*I_e)*

AC miniature circuit breakers are normally suitable for single- and three-phase supplies up to a rated voltage of 240/415 V and AC-DC MCB's additionally for direct voltage supplies up to rated voltages of 125 V, 220 V or 440 V depending on the number of poles.

In addition to the quality of releasing according to the tripping characteristic, a key feature of MCB's is their rated switching capacity. They are assigned to switching capacity classes, which indicate the maximum size of short-circuit current that can be handled. Standard values under IEC 60898 are 1’500, 3’000, 4’500, 6’000, 10’000, 20’000 and 25’000 A.

When selecting a MCB to protect cables and conductors, the permissible let-through-$I^2 \cdot t$ values for conductors must be respected. They may not be exceeded during clearing a short-circuit. Therefore the $I^2 \cdot t$ values in relation to the prospective short-circuit current are important characteristic of MCB’s.

In some countries, miniature circuit breakers are classified according to the permissible $I^2 \cdot t$ values. According to the “Technical Connection Conditions” (TAB) of the German power utilities (EVU) for example only MCB’s with a rated switching capacity of at least 6’000 A and the energy limitation Class 3 may be used for selectivity reasons in distribution boards of domestic and utility buildings behind the meter. For industrial applications a switching capacity of 10’000 A is usually required.

4.2.3.3 Installation of Miniature Circuit Breakers, safety clearances

See also Section **4.2.2.5**.

MCB’s as components of installation systems are usually designed so that compliance with safety clearance requirements is assured when arranged conform to the system structure.

4.2.4 Motor protection relays (overload relays)

Overload relays are used to protect electrical equipment, such as 3-phase AC motors and transformers, against excessive temperature rise and measure the current to determine the temperature-rise and danger to the object to be protected. Protective shutdown is performed via the motor switchgear – usually a contactor.

4.2.4.1 Thermal motor protection relays

Principle of operation

Thermal motor protection relays contain three bimetal strips together with a trip mechanism in a housing made of insulating material. The bimetal strips are heated by the motor current, causing them to bend and activating the trip mechanism after a certain travel which depends on the current-setting of the relay. The release mechanism actuates an auxiliary switch that breaks the coil circuit of the motor contactor (**Fig. 4.2-10**). A switching position indicator signals the condition “tripped”.

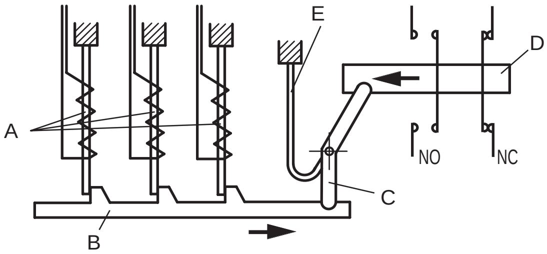


Fig. 4.2-10
Principle of operation of a three pole thermally delayed bimetal motor protection relay with temperature compensation
A = Indirectly heated bimetal strips
B = Trip slide
C = Trip lever
D = Contact lever
E = Compensation bimetal strip

The bimetal strips may be heated directly or indirectly. In the first case, the current flows directly through the bimetal, in the second through an insulated heating winding around the strip. The insulation causes some delay of the heat-flow so that the inertia of indirectly heated thermal relays is greater at higher currents than with their directly heated counterparts. Often both principles are combined. For motor rated currents over approx. 100 A, the motor current is conducted via current transformers. The thermal overload relay is then heated by the secondary current of the current transformer. This means on one hand, that the dissipated power is reduced and, on the other, that the short-circuit withstand capacity is increased.

The tripping current of bimetal relays can be set on a current scale – by displacement of the trip mechanism relative to the bimetal strips – so that the protection characteristic can be matched to the protected object in the key area of continuous duty.

The simple, economical design can only approximate the transient thermal characteristic of the motor. For starting with subsequent continuous duty, the thermal motor protection relay provides perfect protection for the motor. With frequent start-ups in intermittent operation the significantly lower heating time constant of the bimetal strips compared to the motor results in early tripping in which the thermal capacity of the motor is not utilized.

The cooling time constant of thermal relays is shorter than that of normal motors. This also contributes to an increasing difference between the actual temperature of the motor and that simulated by the thermal relay in intermittent operation (**Fig. 4.1-3** Section **4.1.2.1**). For these reasons, the protection of motors in intermittent operation is insufficient.

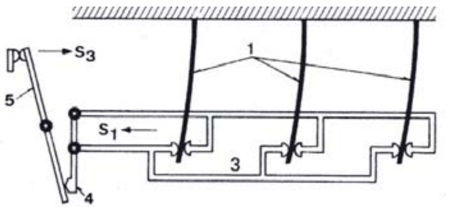
Temperature compensation

The principle of operation of thermal motor protection relays is based on temperature rise. Therefore the ambient temperature of the device affects the tripping specifications. As the installation site and hence the ambient temperature of the motor to be protected usually is different from that of the protective device it is an industry standard that the tripping characteristic of a bimetal relay is temperature-compensated, i.e. largely independent of its ambient temperature (**Fig. 4.1-5**). This is achieved with a compensation bimetal strip that makes the relative position of the trip mechanism independent of the temperature.

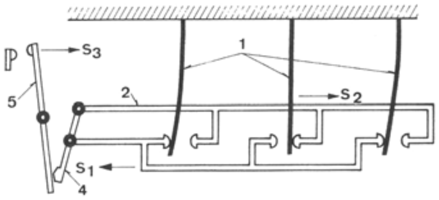
Sensitivity to phase failure

The tripping characteristic of three-pole motor protection relays applies subject to the condition that all three bimetal strips are loaded with the same current at the same time. If, when one pole conductor is interrupted, only two bimetal strips are heated then these two strips must alone produce the force required to actuate the trip mechanism. This requires a higher current or results in a longer tripping time (characteristic curve c in **Fig. 4.2-13**).

If larger motors (≥ 10 kW) are subjected to these higher currents for a longer time, damage should be expected (see Section **4.1.2.4.3**). In order to also ensure the thermal overload protection of the motor in the cases of supply asymmetry and loss of a phase, high quality motor protection relays have mechanisms with phase failure sensitivity (differential release).



Tripping with three-pole load



Tripping with two-pole load, the middle bimetal strip being unheated

1 = Bimetal strip
2 = Phase failure slide
3 = Overload slide
4 = Differential lever
5 = Contact lever
S_1 = Tripping movement at overload
S_2 = Tripping movement with phase failure
S_3 = Opening the trip contact

Fig. 4.2-11
Principle of operation of the differential release for thermal motor protection relays

For this purpose, motor protection relays have a double slide arrangement in the form of a phase failure slide and an overload slide. In the case of phase failure, the de-energized, cooling-down bimetal strip moves the phase-failure slide in the opposite direction to the overload slide. Via a differential lever, this countermovement is converted into an additional tripping displacement (**Fig. 4.2-11**).

In the event of phase failure, this double slide device causes tripping at a lower current than with a 3-phase load (characteristic curve b in **Fig. 4.2-13**).

Single-phase operation

For protection of single phase AC current- or direct current loads, all poles should be connected in series to ensure the force required for tripping the switch mechanism and to prevent tripping by the phase failure protection (**Fig. 4.2-12**).

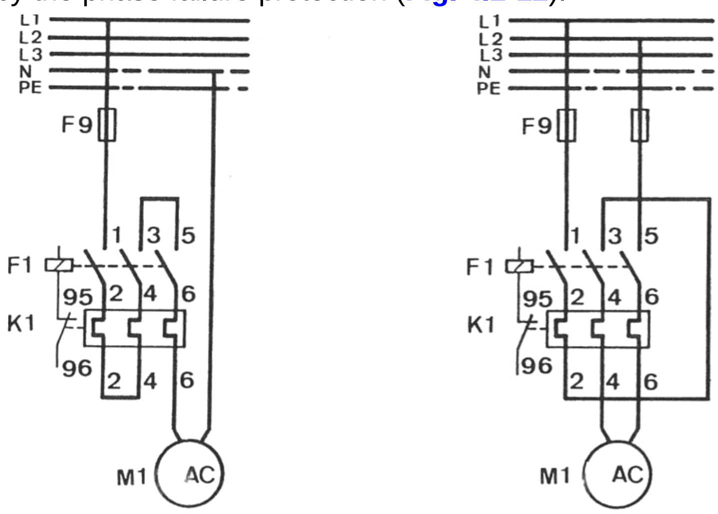


Fig. 4.2-12
Series connection of the poles of the motor protection relay for single-phase operation

Trip characteristics

The trip characteristics reflect the dependency of the tripping time on the tripping current as a multiple of the set current (usually rated operational current I_e of the motor) (**Fig. 4.2-13**). They are stated for symmetrical three-pole and for two-pole loads from the cold state.

The smallest current that causes tripping is known as the ultimate tripping current. Under IEC 60947-4-1 it must lie within certain limits (see Section **4.1.2.2**).

A motor at operational temperature has a lower heat reserve as a motor in a cold state. Allowance is made for this by the characteristic of the motor protection relays. If the motor protection relays are loaded for a longer period with the set current I_e then the tripping times are reduced to around a quarter.

Production, material and calibration tolerances result in tolerances of the tripping times. A tripping tolerance band is therefore assigned to each setting range. According to regulations the tripping times must lie in a tolerance of ±20 % of the stated values from 3 times to 8 times the set current I_e.

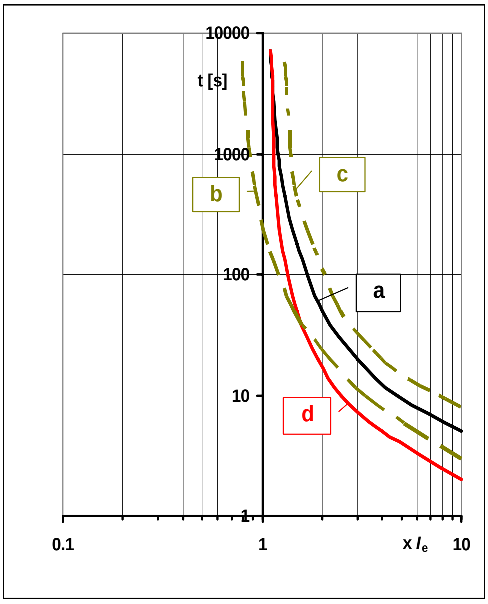


Fig. 4.2-13
Typical trip characteristics of a motor protection relay
- *I_e = Rated current set on the scale*
- *t = Tripping time*

From a cold state:
- *a = 3-pole load, symmetrical*
- *b = 2-pole load with differential release*
- *c = 2-pole load without differential release*

From the warm state:
- *d = 3-pole load, symmetrical*

Resetting after tripping

After tripping, motor protection relays require a certain time before the bimetal strips have cooled-down to the resetting point. This time is known as the recovery time. The relays cannot be reset until this time has elapsed.

The recovery time depends on the magnitude of the current that caused tripping and the tripping characteristic of the motor protection relay. It is around 30 to 50 s after tripping at twice to 6 x the value of the set current.

Modern motor protection relays have an automatic- and hand-reset function. The desired function can be selected at the relays. In hand-reset position, automatic restarting is prevented. Not until the bimetal strips have cooled-down sufficiently can the relays be reset by pressing the reset button. The auxiliary contacts then return to their normal position and prepare such for switching-on the assigned contactor.

As required by IEC and national standards, the motor protection relays are equipped with a free-trip release, i.e. normal protective tripping occurs even when the reset button is pressed.

In the automatic reset position, the contacts automatically reset the bimetal strips when the latter have cooled down.

For safety reasons, motor protection relays with automatic reset should only be used in circuits whose contactors are actuated by momentary contact control (momentary pushbuttons). With hand reset they may also be used in circuits with maintained contact control of the contactors.

For remote resetting of motor protection relays, reset magnets are available that can be mounted onto the motor protection relays.

Test function and O-button

With the test function, the proper operation of the auxiliary contacts and of the connected control circuit of an overload relay ready for service can be tested. This function simulates the tripping of the relay.

With the O-button, the NC contact is opened for as long as the button is pressed. By this means the contactor connected in series and hence the motor can be switched off. This function is often used for simple starters in small housings.

Short-circuit withstand capacity

See also Section **2.3.4.5**. In accordance with IEC 60947-4-1, motor protection relays must be protected against short-circuit so that they are either rendered inoperational by the short-circuit current and have to be replaced (Coordination type 1) or their full operational capability is retained (Coordination type 2). The thermal motor protection relays must be protected against damage by short-circuit currents by circuit breakers or fuses. The fuse values for the respective coordination-type can be obtained from the technical documentation. The short-circuit withstand capacity of directly heated overload relays is higher than that of indirectly heated ones.

4.2.4.2 Electronic motor protection relays

Electronic motor protection relays include a wide range of devices for the protection and the optimized operation of motors and plants. Due to this variety, it is only possible below to consider a few key aspects that are important in the selection and use of these relays. Section **4.1.2.4** shows a selection of functions that are offered by electronic motor protection relays. The range of devices extends from simple and economical designs that are intended for use instead of thermal (for example bimetal) motor protection relays up to very complex devices with a variety of functions, communication links etc.

4.2.4.2.1 Principle of operation

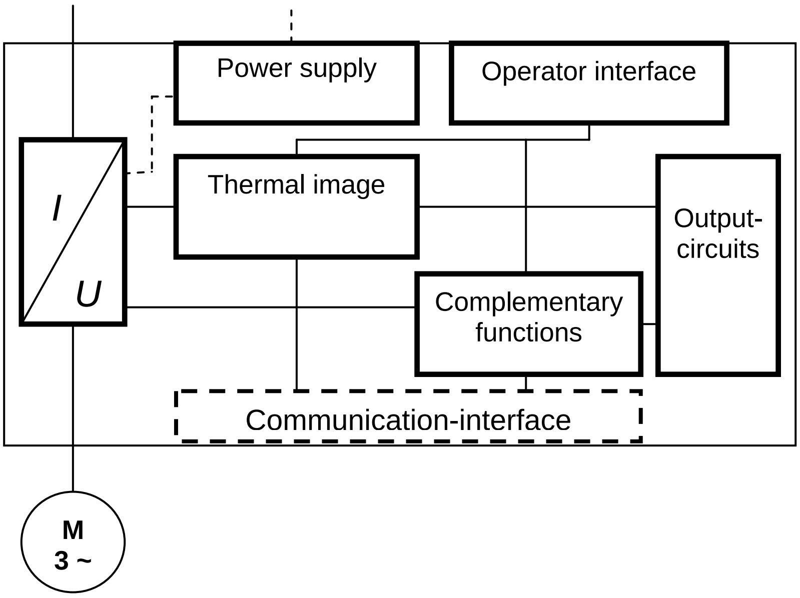


Fig. 4.2-14
Basic functional modules of electronic motor protection relays

Current measurement

For the processing in the electronic circuits, the motor current is measured and converted into an electronically compatible signal. Depending on the principle of operation of the electronics, this signal may be analog (more commonly in simple devices) or digital (in complex devices). Current transformers or magnetic field sensors (for example Hall sensors) are most commonly used for measurement. As the signals are processed electronically, virtually no control signal power is drawn. This results in low heat losses that facilitate control cabinet climate control, which is a major advantage of electronic motor protection relays.

Another advantage of electronic signal processing is the wide current ranges of the devices, which leads to a considerable reduction in the number of versions in comparison to thermal motor protection relays and which simplifies planning and inventory. In addition they usually have a higher precision of the ultimate tripping current thanks to the narrow tolerances of the components used. IEC 60947-4-1 has made allowance for the technical possibilities of electronic motor protection relays by introducing additional trip classes (**Tab. 4.1-3**).

Depending on the principle of current measurement, there are restrictions with respect to the permissible frequency range. When current transformers are used, frequencies significantly below the supply frequency are not acceptable because of saturation, especially applications with direct current are not possible. Applications with variable frequency drives require separate consultation.

The short-circuit withstand capacity of the main circuits is usually very high. Exceptions can be versions with small rated currents, if conductors with small cross-sections are used.

Power supply / internal supply

Simple electronic motor protection relays that are intended as substitutes for bimetal thermal relays obtain the supply for the electronic circuits directly from the measuring circuit and hence require no supply by a separate control voltage. The simplicity of application carries with it a restriction to the basic functions of motor protection – basically to thermal protection and the phase failure protection. In case that other protective functions are offered it should be noted that setting up an internal supply can take a certain time during which these functions are not available.

Complex electronic motor protection relays require a separate control voltage supply that for example can also be provided via the communication link.

Thermal simulation

Thermal simulation, i.e. the simulation of motor heating based on the measured motor current is in simpler relays usually performed on the basis of a single-body replica similar to that of a bimetal relay. Complex devices often also use more complex thermal replicas that more closely simulate motor heating and for example make allowance for the differing cooling characteristics of running and stationary motors. This increases suitability for intermittent operation. Motor protection relays without thermal memory should be marked in accordance with IEC 60947-4-1 as such (on the device) (see also Section **4.1.2.2**).

Top class devices also often take into account the influence of asymmetrical supply on motor heating (see also Section **4.1.2.4.2**).

An important advantage of electronic motor protection relays is the tripping time at high overcurrents (motor starting). Realizing various trip classes (**Tab. 4.1-3**) is a simple matter electronically. The wide tolerance band of the individual classes needs not be used to the full and the tripping times are usually close to upper class limit. This means that relays are well suited for heavy-duty starting applications. In complex relays the trip class (tripping time at $7.2 \cdot I_e$) can often be adjusted and can thus be adapted to the motor and the application.

The phase failure protection usually results in electronic motor protective devices in briefly delayed (a few seconds) tripping, as the loss of a phase can immediately be recognized in the measured signals. The short delay serves to prevent ghost tripping, for example due to short interruptions of the power supply.

Additional functions

Section **4.1.2.4** provides an overview of functions that are often offered by electronic motor protection relays. The range of options is wide and the documentation for the respective devices is definitive in individual cases.

An advantage of electronic motor protective devices is the availability of various functions in a single device and access to device-internal signals. Thus for example current-measuring motor protective devices with inputs for temperature sensors are available.

Outputs – for example for the measured motor current – make separate measuring circuits unnecessary and in particular access to the “temperature state” of the thermal replica allows the devices to be integrated in the control environment. Thus protective tripping can be avoided by the issue of early warnings or – as far as compatible with the processes – the motor loading can be controlled in accordance with measured temperature rise. Integration in the communication system turns the motor protective device into an integrated control component.

Memory functions may be useful for debugging after protective shutdowns or for maintenance. For example the operating data before a protective shutdown can be captured or statistical data on the operation of the drives collected. Such data is frequently offered by microprocessor-based devices.

4.2.4.3 Thermistor protection relays

See also Section **4.1.2.3**.

4.2.4.3.1 Relays for PTC sensors

PTC sensors (**P**ositive **T**emperature **C**oefficient) are most frequently used in low-voltage motors for sensing the windings temperatures. Their resistance increases steeply (**Fig. 4.2-15**) at the rated operating temperature TNF which makes it possible to provide simple and economical tripping devices. The sensors – normally 1 per phase – are imbedded by the motor manufacturer in the windings and are connected in series to terminals. The rated operation temperature TNF is selected in accordance with the insulation class. If early warning before tripping is required it is possible to install a second set of temperature sensors with lower operation temperature that are connected to a separate tripping device.

In order to ensure the proper functioning of the protection system modern trip devices monitor their measuring loops for short-circuits and interruption.

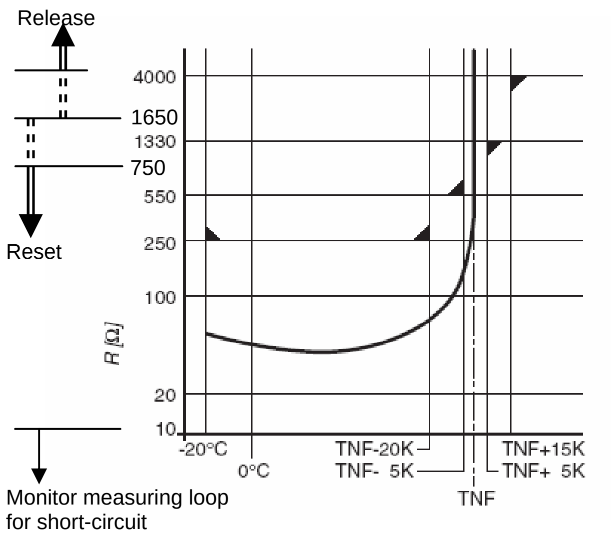


Fig. 4.2-15
Resistance-temperature characteristic of a Type A PTC sensor and threshold values of the tripping devices in accordance with IEC 60947-8 ed. 1.1. (TNF = rated operation temperature)
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4.2.4.3.2 Relays for NTC sensors

The characteristics of NTC sensors (**N**egative **T**emperature **C**oefficient) show decreasing resistance with increasing temperature. They are used in special cases and require tripping devices with an adjustable response threshold. With one set of sensors, early warning and tripping can be realized.

4.2.4.3.3 Metal resistance sensors

These sensors – for example Pt 100, Ni 100, Ni 120, Cu 10 – are especially suitable for medium and high voltage motors. They are used for measuring temperatures of windings and other machine parts, such as bearings. Tripping devices have a correspondingly larger number of inputs. The operation and warning levels can be adjusted. Frequently important temperature values are also shown on displays.

5 Control circuits

5.1 *Utilization categories*

IEC 60947-5-1 defines the requirements for electromechanical devices for control circuits. In the utilization categories AC-12 to AC-15 and DC-12 to DC-14 reference applications are defined for switchgear in control circuits that facilitate device selection (**Tab. 5.1-1**; see also **Tab. 1.1-1** in Section **1.1**).

Kind of current	Category	Typical applications	Relevant IEC product standard
Alternating current	AC-12 AC-13 AC-14 AC-15	Control of resistive loads and solid state loads with isolation by optocouplers Control of solid state loads with transformer isolation Control of small electromagnetic loads (≤72 VA) Control of electromagnetic loads (>72 VA)	60947-5-1
Direct current	DC-12 DC-13 DC-14	Control of resistive loads and solid state loads with isolation by optocouplers Control of electromagnets Control of electromagnetic loads having economy resistors in circuit	60947-5-1

Tab. 5.1-1
Utilization categories for control circuits in accordance with IEC 60947-5-1 ed. 3.0

The standard also defines the test conditions for the individual utilization categories so that the ratings are defined and are comparable in accordance with the utilization category. In addition to the utilization category, the ratings of a contact include the rated voltage and the rated current or the rated apparent power. When evaluating devices, this data should be compared with that for the load to be switched.

The performance data according to the utilization category specify the maximum load capacity of the switching components. In applications with electronic devices – because of the low level of voltage and current – contact reliability is the main criterion for selection, i.e. the reliability with which the low signal levels are switched. See Section **5.3.5**.

5.2 *Control voltages*

5.2.1 Alternating voltage

Both alternating and direct voltage can be used as control voltages. In the case of alternating voltages, IEC 60204-1 (Safety of Machinery– Electrical equipment of machines) stipulates that the control voltage must be supplied via transformers with separate windings. When several control transformers or a control transformer with several secondary windings are used it is recommended to arrange the circuits so that the secondary voltages are in phase. Transformers are not mandatory for machines with only one (1) motor starter and/or a maximum of two control devices. The maximum rated voltage is 277 V, common preferred values are 110 V and 230 V. Also 24 V is increasingly used.

Among the good reasons for using control transformers is that in the case of a short-circuit in the control circuit the prospective short-circuit current is limited by the impedance of the control transformer and hence welding of the control contacts can largely be avoided. This is also reflected in the fact that the short-circuit tests for control contacts in accordance with IEC 60947-5-1 are carried out at a prospective short-circuit current of 1000 A.

The selection of the control voltage has among other things an influence on the size of the currents flowing. In this regard, special attention should be paid to the pick-up currents of large magnetic loads (for example of large contactors). Switching contacts and conductor cross sections should be selected and rated correspondingly to comply with loading limits and to keep the voltage drop within the permissible limits.

5.2.1.1 Control transformers for contactor controls

In accordance with IEC 60947-4-1 contactors have a normal control voltage range of 85 % – 110 % the rated control supply voltage, i.e. they reliably close and stay closed within these voltage limits. Often contactors are available with an extended control voltage range, for example 80 % – 110 % or 115 %. Because of the high pick-up currents of AC magnets – especially when using large contactors and when several contactors are switched simultaneously – it should be ensured that the voltage does not fall below the lower limit. This could result in contactors not completely closing and the high pick-up current flowing for an extended period. The consequence can be burning of the coil and / or welding of the main contacts.

For control transformers supplying electromagnetic loads such as contactors, an important selection criterion is the short-term power $P_{S(S6)}$. The drop in secondary voltage in comparison to the rated voltage may be no more than 5 % at this power rating. The peak load of the control transformer should be determined in each individual case and the control transformer should be selected considering the prospective supply voltage variations. Often the worst case scenario is to assume that the largest contactor must reliably close at a certain basic load of the transformer.

5.2.1.2 Frequencies < 50 Hz and > 60 Hz

Normal AC magnets are rated for 50 Hz or 60 Hz. Usually the voltage specifications for both frequencies are provided in the technical documentation. Often dual frequency versions are also available, i.e. the devices can be used at the same rated voltage with 50 Hz and 60 Hz supplies. Dual frequency designs are advantageous for the export industry, thus the same devices can be used in all markets – subject to adjustment of the voltage magnitude (tapping of the control transformer). For controls that do not require this flexibility, it is recommended to choose contactors for one (1) rated frequency as the tolerance range of the control voltage and the mechanical life span are then optimized.

For applications in railway transport systems at 16 2/3 Hz and applications at 400 Hz (airports, military), devices with direct current magnets must be used and – in case that a direct current supply is not available – the alternating voltage rectified.

5.2.2 Direct voltage

Direct voltage is used as a control voltage in a large and growing range of applications. Typical applications are installations on vehicles (for example refrigeration systems), stationary battery-powered systems (power utility installations) and constantly growing areas of electronic controls in industry and building technology.

Preferred direct voltages are 24 V (industry, vehicles), 48 V (vehicles) and 110 V, 220 V … 250 V (power utilities, high-voltage batteries, energy regeneration).

Given the wide range of battery voltages on vehicles (overcharging and complete discharge) contactors with an extended voltage range are offered (for example 0.7 … 1.25 U_N).

Quality of direct voltage

When direct voltage is used as a control voltage, in addition to the tolerance range of the voltage attention should be paid to its harmonic content (ripple content). Battery powered systems are in this regard an ideal voltage source without harmonics. Also switched power supplies produce well smoothed direct voltages.

If the direct voltage is obtained from alternating voltage by rectification, the harmonic content depending on the circuit may be relatively large and must be considered. In these cases it should always be remembered that the arithmetical average voltage is the critical quantity for the pull-in performance of conventional electromagnets. Two-way rectification (Graetz rectifier) is usually permissible for supplying conventional contactor coils; also 3-phase bridge circuits with a ripple of around 5 %.

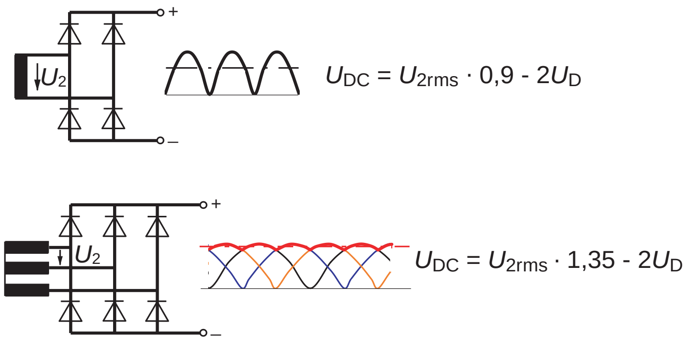

Fig. 5.2-1
Rectifier circuits for supplying electromagnetic loads

For controlling and supplying contactors with electronic coil control it should be noted that the instantaneous value of the direct voltage may not fall below a certain minimum value. This is in regard to the proper functioning of the electronic circuit. The specifications of the product in question with respect to the quality of the direct voltage should be observed. Especially with large contactors and a small control voltage (for example 24 V), the current consumption of the devices may short-term extend way beyond the 10 A range. In such cases it should be ensured that correspondingly powerful supply units are used and that the voltage drops on the connections between the supply and contactor are as small as possible (short lines, large cross sections, no loops, good quality terminations). Unstabilized supply devices with two-way rectification and smoothing capacitor soon reach their limits in these applications.

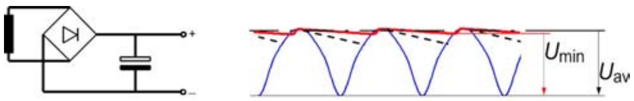

Fig. 5.2-2
Simple Graetz rectifier with capacitive smoothing result at higher load currents to strong discharge between the half-cycles (dashed line) that can cause malfunctions in electronically controlled contactors and other electronic devices.

5.3 Switching contactors

5.3.1 Alternating current magnets

5.3.1.1 Conventional alternating current magnets

Alternating current magnetic drives are characterized by a high pull-in current that flows when the magnet system is open and is determined by the low coil impedance (large air gap). The utilization categories AC-14 and AC-15 take this characteristic into account. The high pull-in current surge thermally loads the coil and restrict the permissible frequency of operation. Especially at small control voltages with large contactors, attention must be paid to voltage drops in the control circuit to ensure reliable switching.

When contactors are switched off, the inductance is large because of the small size of the residual air gap. This results in a corresponding arcing of the control contacts and to switching transients. External overvoltage protection measures may be required (see Section **5.3.3.1**).

5.3.1.2 Electronic coil control

By means of electronic circuits, the operating conditions for contactor magnet systems can be optimized and the operation optimally adjusted to user requirements. Thus the magnet system can be isolated from voltage variations so that the current drawn is optimized and the pull-in and drop-out values clearly defined. As required by the user, control can be performed conventionally by application of a control voltage or by a PLC signal, either directly or via a control input.

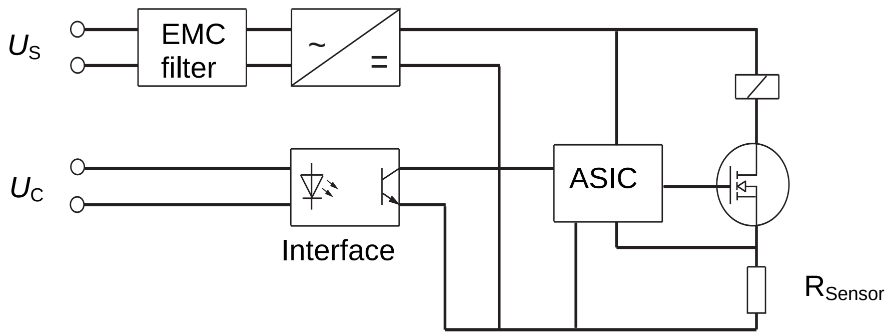

Fig. 5.3-1
Example of electronic control of a contactor coil with separate control input
U_S *control supply voltage*
U_C *control voltage (PLC)*

The advantages of electronically controlled contactor magnet systems:

- Wide control supply voltage range
- Low current consumption
- Clear pull-in and drop-out voltages
- Undervoltage reliability
- Direct PLC control
- Integrated overvoltage protection circuit
- EMC compatible
- Small size (usually same as contactors with conventional drive)
- Low noise development

5.3.2 Direct current drives

5.3.2.1 "Conventional"

With direct current, larger magnet systems with specially shaped poles are required to generate the forces needed for pulling in contactors and to optimize the holding energy. This results, on the one hand, in a large depth of devices and, on the other, in switching on gentler and in comparatively low current consumption during pulling-in. The pull-in power is the same as the holding power. The loading of the control contacts during circuit breaking is relatively high because of the high inductance of the coils and is taken into account by utilization category DC-13.

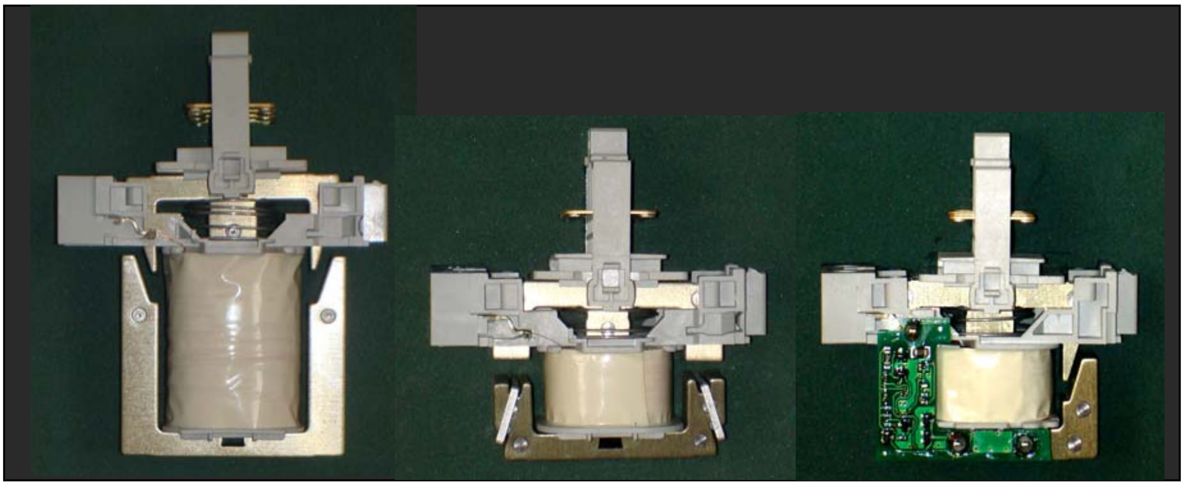

Fig. 5.3-2
Conventional direct current magnet system in the comparison to an alternating current magnet system and a magnet system with electronic coil control (same size for alternating and direct current)

5.3.2.2 Double winding coils

Direct current contactors with double winding coils are contactors with alternating current magnets and a pull-in and holding coil. The size is the same as that of alternating current contactors. The contactors switch on by means of a pull-in winding with low impedance and a correspondingly higher pull-in current. After the magnet circuit is closed, the excitation is switched over by an auxiliary switch to the lower holding power. The auxiliary switch can be integrated in the device or – usually with smaller contactors – be externally mounted.

5.3.2.3 Electronic coil control

Electronic coil control is also available for contactors with direct current supply. The characteristics and advantages are similar to those with alternating current supply.
See Section **5.3.1.2**.

5.3.3 Electromagnetic compatibility and protective circuits

Conventional switchgear without active electronic circuits such as switched power supplies for controlling contactor coils is considered from an EMC viewpoint as belonging to a normal control environment. Although these devices can short-term generate very high and steep overvoltages, from an EMC perspective no countermeasures are required. The levels of immunity tests for industrial applications are set so that other devices usually function reliably at this level of interferences.

Like all other electronic devices, devices with active electronic circuits such as contactors with electronic coil control are subject to the relevant immunity and emission tests. For industrial switchgear the levels correspond to the **Environment A "Industry"** (high immunity against interferences, high interference emissions). If devices such as contactors with electronic coil control are used in **Environment B "Domestic /Commercial/Light industry Installations"** (low interference immunity, low emissions), it should be ensured that the devices have also been tested for these areas of application. On the other hand, devices for the Environment B are not suitable and permitted for use in industrial applications with their higher levels of interference.

In addition to the selection of devices for the given environment, the instructions of the respective device manufacturer with respect to the installation and connections (for example shielded cables) must be observed to achieve EMC compatibility of the switchgear assembly.

5.3.3.1 Protective circuits in coil circuits

When switching magnetic loads with high inductance such as for example contactor coils, in spite of the above considerations, switching transients with magnitudes of several kV and with rise-times in the range of μs to ns can occur that may interfere with the proper functioning of other devices. During the opening of the controlling contacts, there occur repeated restrikes (shower discharges), as the inductance of the coil maintains the current flow and the opening contact does not instantaneously attain its full withstand voltage (**Fig. 5.3-3**). These shower discharges also increase wear on the switching control contact. With respect to the interference effect, it is not only the size of the overvoltage that is generated that is critical but also, in view of the extremely short reaction times of electronic circuits, its rise and fall time. Rapid signals couple via stray capacitances with other signal circuits.

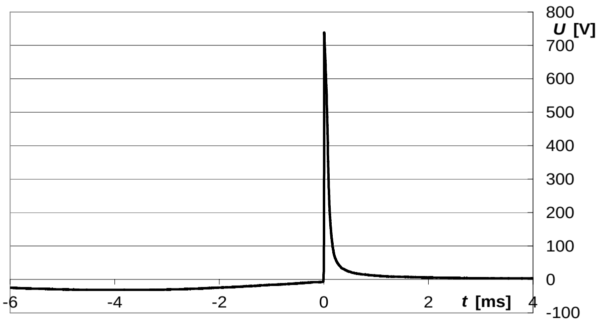

Fig. 5.3-3
Oscillogram of the voltage characteristic during circuit breaking of a 24 V coil without protection circuit

The best countermeasure is to deal with the interference at the source. To this end suppressor modules are offered for interference-producing coils, designed as plug-on or wired add-ons or integrated in the contactor. **Tab. 5.3-1** provides a summary of the alternatives and their most important features. Measures that only limit the amplitude of the overvoltage are also effective with respect to dynamic interference (to a limited extent) as they reduce the duration of the shower discharges and limit their amplitude.

Technical solution		Suitable for		Limitation of		Functional features
		a.c.	d.c.	Amplitude	Rise-time	
RC module		X	X	X	X	Limitation-effect depends on the component sizing
Varistor		X	X	X		Amplitude limitation at the operation voltage of the varistor. Max. voltage rise $\hat{U}_C+U_V$
Diode		---	X	X		To be connected with correct polarity. Extended drop-out time. Max. voltage rise U_C
Bidirectional Z-diode			X	X		Small extension of the drop-out time. Max. voltage rise U_C+U_Z

Tab. 5.3-1
Protective circuit measures for contactors
U_C Control voltage
U_V Varistor operation voltage
U_Z Limiting voltage of the Z diode

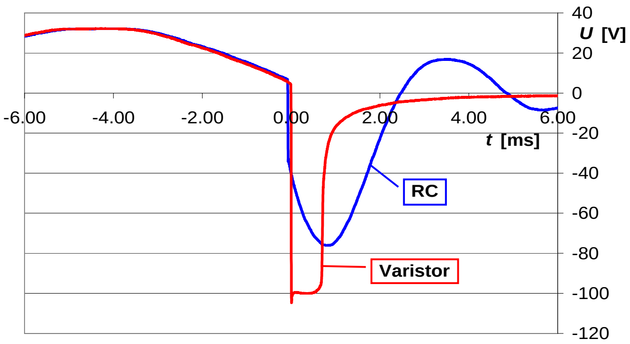

Fig. 5.3-4
Oscillogram of the voltage characteristic during circuit breaking of a 24 V coil with protection circuits

5.3.4 Effect of long control lines

5.3.4.1 Voltage drop

In accordance with IEC 60947-4-1 and IEC 60947-5-1, the normal control voltage range of power and control contactors lies between 85 … 110 % of the rated control voltage. Within these limits contactors pull-in perfectly. Frequently contactors are offered with an extended control voltage range, thus for example with contactors with electronic coil control. The technical documentation of the devices used is definitive.

At small control voltages and with long control lines, the voltage drop across the lines to the contactor (both out-going and return conductors should be considered!) can be so big that pulling-in reliably is no longer guaranteed. In addition to burnt coils, another consequence of this may be welding of the main contacts. It must therefore be ensured that taking into account

- Supply voltage variations
- Voltage drop at the control transformer at peak load (see Section **5.2.1.1**) and
- Voltage drop across the control lines

the minimum pull-in voltage is always guaranteed.

For the voltage drop across the control lines the following applies approximately:

$$u_R = \frac{S \cdot 100 \cdot l}{U_C^2 \cdot \kappa \cdot A} \text{ [\%]}$$

or for the maximum line length at a given permissible voltage drop

$$l_{\max} \approx \frac{u_R}{100} \cdot \frac{U_C^2}{S} \cdot \kappa \cdot A$$

l	Line length (supply and return line) [m]
l_{max}	maximum line length (feeding and return line) [m]
u_R	Percentage voltage drop [%]
U_C	Rated control voltage [V]
S	Pickup power of the contactor [VA]
κ	Conductivity of the conductor material [$m \cdot \Omega^{-1} \cdot mm^{-1}$] = 57 for copper
A	Conductor cross section [mm^2]

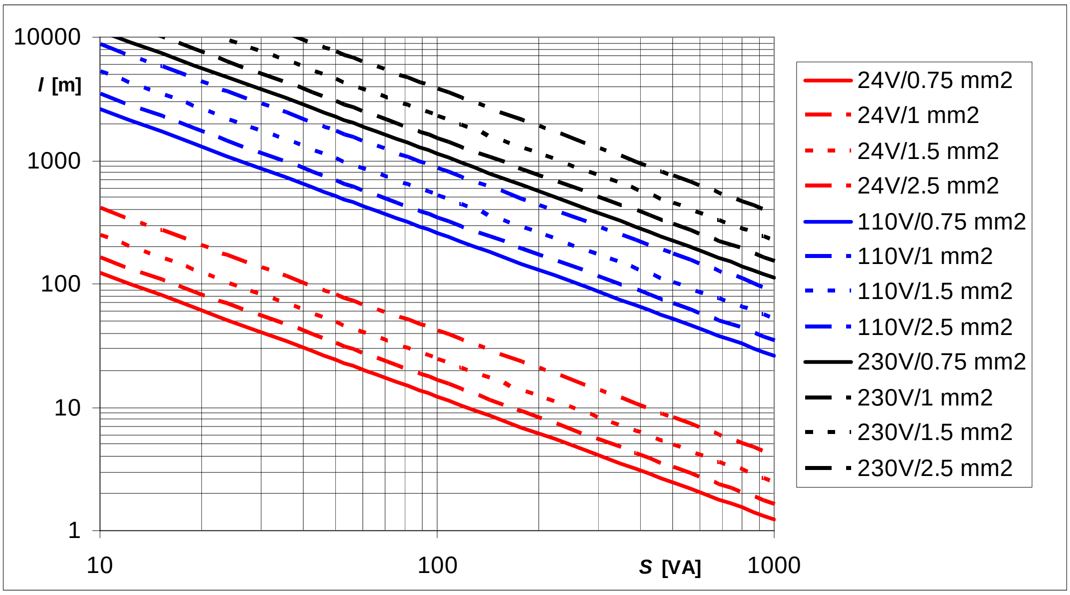

Fig. 5.3-5
Line lengths for a voltage drop of 5 % and copper conductors
l Line length (feeding and return line)
S Apparent power of load

5.3.4.2 Effect of the cable capacitance

With AC controls with long control lines, low coil power ratings of the contactors and high control voltage, depending on the topography of the circuit, the capacitance of the control line can be in parallel to the controlling contact and practically bypass it when it is open. This can mean that when the control contact has opened sufficient current continues to flow via the cable capacitance causing the contactor not to drop out. An example may be a contactor that is controlled by a distantly located sensor (for example limit-switch).

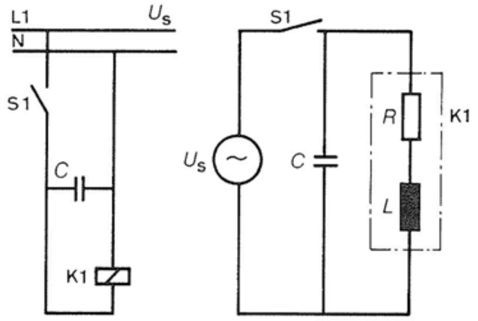

Fig. 5.3-6
When the control contact switches off the cable to the contactor, the capacitance of the line causes at most a slight drop-off delay.

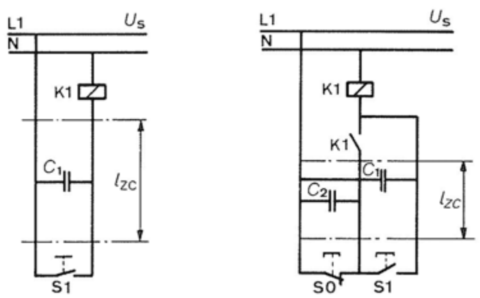

Fig. 5.3-7
If the long control line to the contactor stays live when the control contact is open, the current via the cable capacitance can prevent the contactor from dropping out. With pulse contact control, the capacitance of the lines acts twice, whereby the permissible line length is halved.

A worked example would be

I_H = 0.25 I_{CN}
U_H = 0.6 U_C
cos φ = 0.3
I_H Holding current of the contactor
I_{CN} Rated current the contactor coil
U_H Drop-out voltage of the contactor
U_C Control voltage
cos φ Power factor of the contactor coil (on-state)

The permissible cable capacitance is calculated at 50 Hz approximately to be

$C_Z \approx 500 \cdot S_H/U_C^2$ [μF]

C_Z Permissible cable capacitance [μF]
S_H Holding power at U_C [VA]
U_C Control voltage [V]

At a typical cable capacitance of 0.3 μF/km the permissible line length for maintained contact control is

$$l_z = \frac{500 \cdot 10^3}{0.3} \cdot \frac{S_H}{U_c^2} \text{ [m]}$$

With momentary contact control the line length is halved. Graphic presentation for the control voltages 110 V and 230 V see **Fig. 5.3-8**.

As the cable capacitance is very much dependent on the type of cable, it is recommended in case of doubt to obtain the specific value from the manufacturer or to measure it.

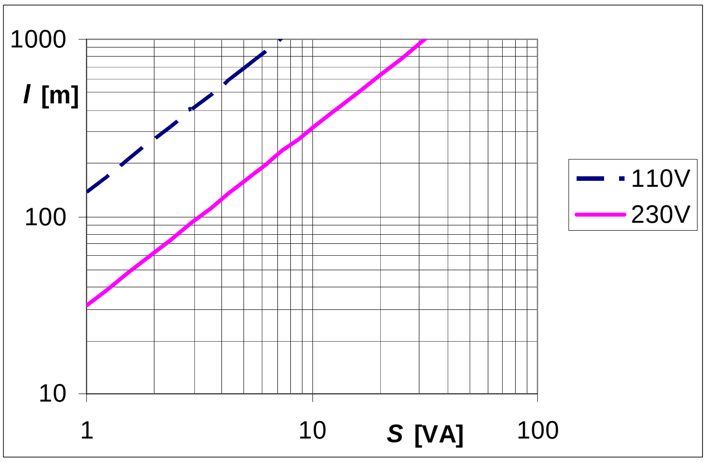

Fig. 5.3-8
Permissible line length in accordance with the above conditions for maintained contact control at control voltages of 110 V and 230 V at 50 Hz
l Line length
S Apparent power (holding power) of the contactor

If there are problems with respect to the permissible line length because of the line capacitance the following measures are possible in accordance with above discussion:

- Application of an additional load (resistor parallel to contactor coil)
- Use of a larger contactor with bigger holding power
- Use of a lower control voltage
- Use of direct voltage

5.3.5 Contact reliability

Electronic devices and circuits as commonly used in industrial applications, for example in PLC control devices and safety relays put high demands on the functional reliability of the controlling contacts, whether auxiliary switches of power switchgear or for example contacts of control units, sensors, function relays etc. The voltage to be switched is usually 24 V or even lower and the switching currents remain in the low mA range. Contacts connected in series (for example to safety relays) are frequently de-energized when they close and open, so that a switching operation under electrical load never takes place.

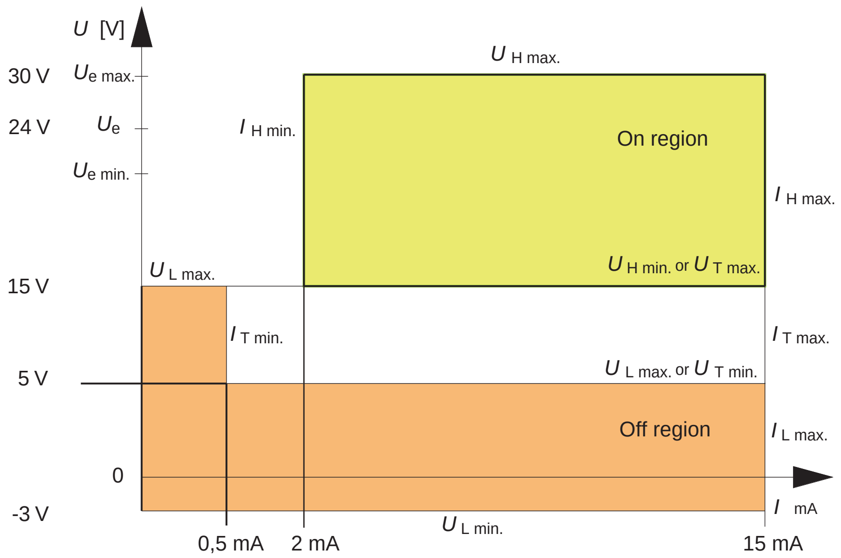

Fig. 5.3-9
Operational range of PLC inputs in accordance with IEC 61131-2 (Programmable controllers – Part 2: Equipment requirements and tests) and IEC 60947-1 Annex S (Digital inputs and outputs) for contact-inputs (digital input type 1) at a rated control voltage of 24 V. The contact load for ON can be between 30 and 15 V and 15 and 2 mA.
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While at switching higher voltages and loads, a cleaning process by the arc takes place with every switching operation, with small signals special measures are required to ensure a high quality of contact making, that is to guarantee a high degree of contact reliability. At a typical PLC input resistance of several kΩ it is not a matter of mΩ as in power contacts. Good contact making can be for example prevented by

- Films on the contact surfaces, originating from reactions with ambient gases (for example oxidation, formation of sulphide layers) or from deposits of volatile components of the ambient atmosphere (e.g. that originate from production processes at the location or effluvia from plastics in the switchboard cabinet). Such films can usually only be identified with special devices and the cause is often hard to determine and eliminate.
- Films on the contact surface that are caused by migration of metal material from the contact base and often interact with the first point and the switching operation.
- Contamination of the contact surface that can emanate from the environment (open switching cabinet doors during commissioning!), from the interior of the switching cabinet or from the device itself. A problem that should not be neglected is the generation of foreign particles by the operation of the devices itself, for example due to abrasion.

Provisions for ensuring good contact reliability include

- Selection of suitable contact materials (basic material and possibly surface coatings such as gold)
- Avoidance of internal sources (for example materials and/or abrasion) that could have an adverse effect on contact reliability.
- Use of high contact pressures that are able to break through tarnishing films, e.g. by appropriate shape of the contact surface.
- Relative movement of the contact surfaces during circuit making that break through tarnishing layers and can remove contamination. It should be noted that this can cause abrasion, which may have a negative effect on life span and possibly contact reliability .
- Use of multiple contacts (double contacts, H-contacts), with which the likelihood of good contact making is increased by parallel connection of the contact points.
- Avoidance of too low contact loading and of series connection of a bigger number of contacts.

- Avoidance of interfering external influences (foreign particles, chemical effects) at the site of installation.

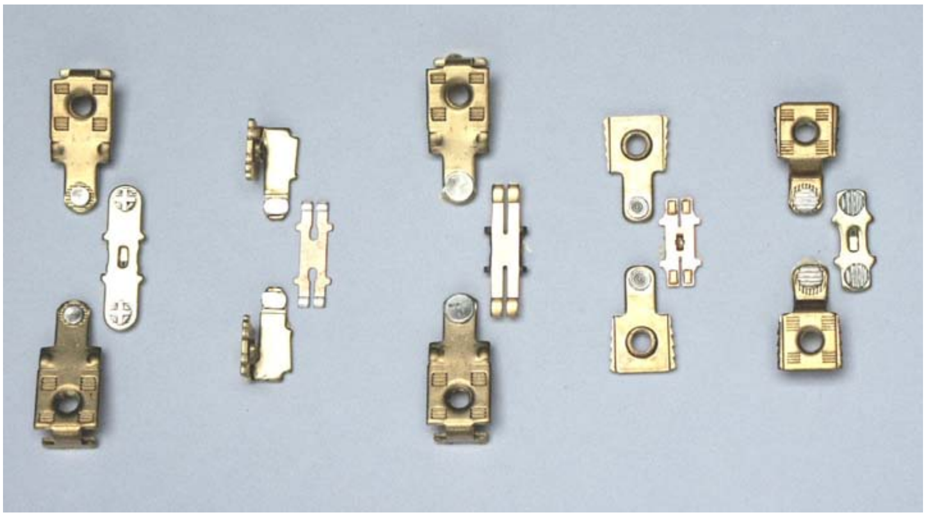

Fig. 5.3-10
Double contacts, increased contact pressure (for example by riffling of the contact surface) and gold-plating are some of the possible approaches to obtain good contact reliability

The attainment of satisfactory contact and hence functional reliability requires appropriate measures by the device manufacturer and the user. On the user side, the selection of a suitable contact design for the respective application from the manufacturer's product range, compliance with manufacturer specifications and the measures listed above will have a beneficial effect on contact reliability. Care is required with all kinds of chemical substances in the switching cabinet. Thus while contact sprays may be good for oxidized sockets – for switching contacts they are poison!

Universal control contacts can be used over a wide range of voltages and powers. They are suitable both for switching contactor coils at 230 V or 110 V and for control of PLC's at 24 V. To achieve a high degree of contact reliability, contacts should normally not be connected in series at the small control voltages as common with PLC control. With contacts that are specially designed for low signal levels it should be noted that even single switching operations at higher power levels can destroy the surface structures and hence the electronic-compatibility will completely be lost or at least strongly reduced.

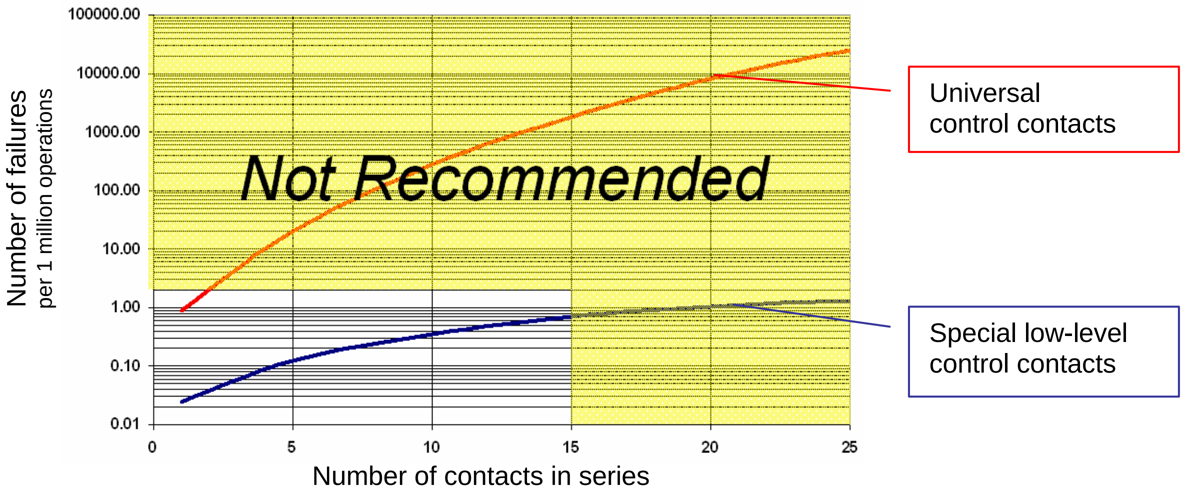

Fig. 5.3-11
Typical contact reliability values at 15 V/5 mA of universal control contacts and special low-level control contacts

6 Considerations when building control systems and switchgear assemblies

6.1 Temperature rise

The temperature of the devices in the switchboard cabinet and that of touchable parts are important factors with respect to operational reliability, life span and personal safety. It depends among other things on the ambient temperature of the switchgear assembly, the heat flow via enclosures, if any, and/or air conditioning, the method of installation of devices (mutual heating, heat abduction, formation of hotspots), wiring (heat-flow via conductors) and last but not least the dissipated heat (load losses) of the devices.

6.1.1 Temperature rise limit values

The relevant standards such as IEC 60947-1 (low-voltage switchgear) and IEC 60439-1 (Low-voltage switchgear assemblies) define upper limits for the temperatures of the relevant constructive parts. IEC 60204 (Safety of machinery - Electrical equipment of machines) refers to IEC 60439-1.

Part	**Temperature-rise limits 1)**	**Reference (ambient) temperature**	**Temperature-limit (absolute) 1)**
Metallic manual operating means	15 … 25 K	40 °C	55 … 65 °C
Non-metallic manual operating means	25 … 35 K	40 °C	65 … 75 °C
Metallic parts intended to be touched but not hand-held	30 … 40 K	40 °C	70 … 80 °C
Non-metallic parts intended to be touched but not hand-held	40 … 50 K	40 °C	80 … 90 °C
Metallic surfaces not intended to be touched	40 … 50 K	40 °C	80 … 90 °C
Non-metallic surfaces not intended to be touched	50 … 60 K	40 °C	90 … 100 °C
Terminals for external connections (Cu silver- or nickel-plated)	70 … 80 K	40 °C	110 … 120 °C
1) The higher values apply for used devices and for parts which are not intended to be touched or operated frequently respectively.			

Tab. 6.1-1
Temperature-rise limit values in accordance with IEC 60947 and IEC 60439

The permissible temperature-rises or temperatures appear in some cases to be high, for example those for the temperature-rise of terminals. This limit value is based on the connection of conductor material with a permissible continuous insulation temperature of 70 °C. The high temperature of the connection point itself is permissible as after only a short distance, the conductor temperature starts to decrease due to the heat flow from the terminal point via the connected line. The conductor material (cable, busbar etc) acts as a thermal aerial assisting in the heat dissipation process. Experience gained over many decades and with billions of terminal points confirms the correct choice of the limit values.

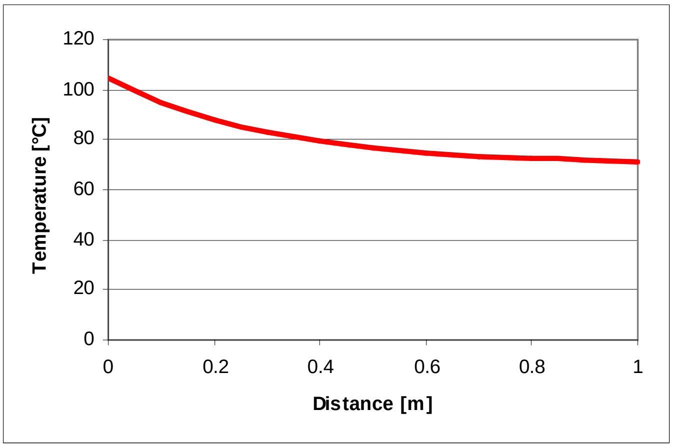

Fig. 6.1-1
Typical decrease in conductor temperature with increasing distance from the terminal

Decisive for the functional reliability of devices, their life span or the risk of accidents, is not the temperature-rise but the absolute temperature. The standards define temperature-rise limits for practical reasons so that tests can be performed in a laboratory environment. The reference ambient temperature in accordance with standards is 35 °C as an average over 24 hours with a maximum value of 40 °C. If the ambient temperature around the devices exceeds these values in actual service – for example because they are installed in a switching cabinet – then their load must be reduced correspondingly so that the permissible absolute temperature values are observed. This especially affects the temperatures of internal parts of devices in respect of the thermal stability of the materials used. For reduction factors, see manufacturers documentation.

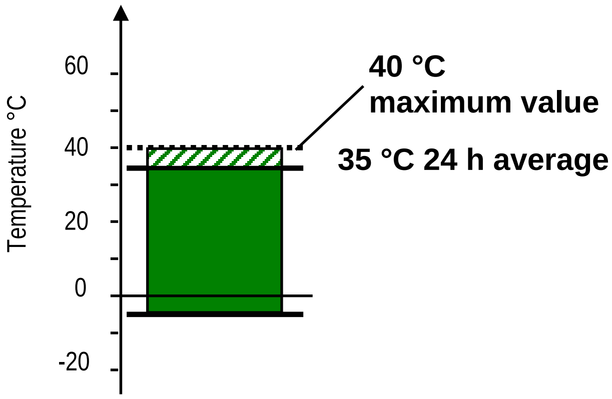

Fig. 6.1-2
The normal temperature range for devices in accordance with IEC 60947 is identical with the normal temperature range for switchgear assemblies in accordance with IEC 60439, in which the devices are installed.

6.1.2 Laboratory test conditions and real practical environment

The temperature-rise test of low-voltage devices and hence the determination of their permissible thermal loads is performed in accordance with standards under precisely defined conditions. This is important to obtain comparable measurement results.

The test conditions are:

- Set-up of device to be tested in open air
- Measurement of the ambient temperature at 1 m horizontal distance
- Connections to the current source and between the terminals with defined conductor cross sections (depending on the rated current)
- Connections to the current source and between the terminals with a minimum length of 1 m up to cross section 35 mm^2, at bigger cross sections 2 m and over 800 A rated current 3 m.

The real application conditions often differ from test conditions. Devices are usually closely mounted next to each other and connected with short conductors. Often the conductors of several circuits are routed closely together so that they compound the heating effect. In addition the devices are usually installed in a housing, the interior of which reaches temperature above the external ambient. It should be noted that the normal ambient temperature range for the devices is identical with the normal ambient temperature range for switchgear assemblies.

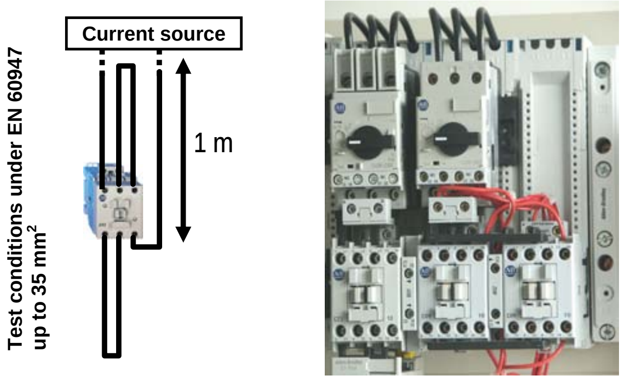

Fig. 6.1-3
The practical conditions with respect to the connections (example on right) differ considerably from the arrangements at type testing.

It is the responsibility of the manufacturer of a switchgear assembly or of a control system to ensure that the prescribed temperature limits are respected under practical conditions. Special attention should be paid to devices that are operated close to the thermal continuous current, in particular to circuit breakers and thermal overload relays. At utilization categories such as AC-3 and AC-4, where the switching capacity of the devices is the most significant selection consideration, heating by the continuous operational current is usually less critical.

6.1.3 Verification of temperature-rise

For control systems and switchgear assemblies, verification of temperature-rise is generally required. This can be based on measurements (for example with series-produced devices and systems and modular equipment), or on calculation, or be derived from measured systems. For calculating the temperature-rise of switchgear assemblies, IEC 60890 provides a method that is relatively straightforward for determining the over-temperature in an enclosure if the heat dissipation inside is known. In addition some conditions must be fulfilled, for example a largely uniform distribution of heat sources in the cabinet.

Rockwell Automation has created a very useful tool for calculating the temperature-rise in enclosures and switching cabinets in the form of TRCS (Temperature Rise Calculation Software) based on IEC 60890. TRCS also enables very efficient determination of heat dissipation by components and conductors in the assembly on the basis of their operational data. Experience shows that the contribution of conductors to temperature-rise is significant (up to 50 %), if they are operated close to the rated current and hence to the rated insulation temperature (for example 70 °C).

6.1.4 Important aspects regarding device temperature rise; Recommendations

6.1.4.1 Rated current

For many low-voltage components (for example circuit breakers, load switches, contactors, fuses, conductors), ohmic losses are the main sources of losses. They are proportional to the square of the operational current. The r.m.s. value is definitive. Under variable load conditions (for example intermittent operation) the r.m.s. value can be averaged over time, if the cycle time is shorter that the heating time constants of devices. In the power range up to around 40 A the permissible integration time (= cycle time) is around 15 … 20 minutes.

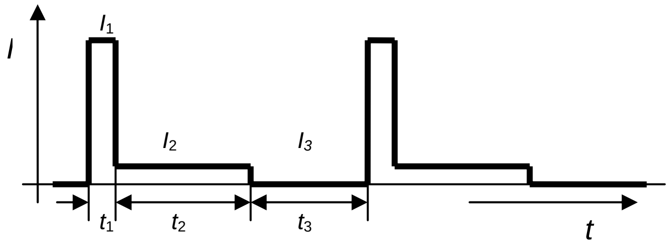

Fig. 6.1-4
Example of calculation of the effective value for intermittent operation of a motor.

$$I_{eff} = \sqrt{\frac{I_1^2 \cdot t_1 + I_2^2 \cdot t_2 + I_3^2 \cdot t_3}{t_1 + t_2 + t_3}}$$

t_1	*Starting time at starting current I_1*
t_2	*Service period at operating current I_2*
t_3	*Interval time at current I_3=0*
$t_1 + t_2 + t_3$	*Cycle time*

As the operating conditions often deviate from those for determining the conventional thermal current in the open air I_{th} (see above), as a general rule of thumb it is recommended not to operate devices at over 80 % I_{th}. At 80 % current, the current-based heat losses (ohmic losses) are reduced to around 64 %.

6.1.4.2 Thermal protective devices

In protective devices such as circuit breakers or motor protection relays with narrow adjustment ranges, the 80 % recommendation can not always be observed as the devices must be set to the rated current of the load to be protected and often the overlap of the current ranges is insufficient. As far as possible, a current range should be selected that enables for a setting and hence operation, in the low to medium range of the scale.

For bimetallic protective devices it should be noted that the heat generated in the bimetal strips required to provide for the quality of protection is roughly the same for all current ranges of a frame size. A 1 A bimetal relay at 1 A generates approximately the same heat as a 10 A bimetal relay of the same size at 10 A.

6.1.4.3 Conductor cross sections

A substantial quantity of heat is removed from the devices via the connected conductors. The larger the cross section the better is the cooling effect.

During the manufacturer's temperature-rise tests, attention is paid to compliance with the temperature-rise limits as of **Tab. 6.1-1,** the temperature rise of internal components used within the devices and their compatibility with the materials used. At increased ambient temperature, for example when the devices are installed in cases or cabinets, larger cross sections of connecting conductors are required than those used in the type tests and those corresponding to the regular installation tables, which are based on an ambient temperature of 30 °C. In practice, selection of a conductor that is "one size up" in cross-section is recommended. This also has the advantage that the heat dissipation in the switching cabinet and the energy consumption of the installation are reduced because of the lower current density in the conductor. If necessary, two conductors can be run in parallel.

With bimetal relays and circuit breakers with bimetallic tripping mechanisms, the cross section of the connected conductor affects the ultimate tripping current. Typically, a larger wire cross section can, depending on the temperature compensation of the bimetal strips, lead in practice to an increase of the ultimate tripping current by up to 5 %. From this point of view it is advantageous, rather than choosing the device with the highest current range of a frame size of bimetal relay or circuit breaker, to choose the next largest frame size.

The selection of conductors with a higher insulation class does not affect the rate of heat-flow out of the devices. For this reason, their cross-section should be the same as those of conductors with a 70 °C limiting temperature.

In the case of busbars it should be noted that, for the same reasons, the load capacity of busbars that are connected to devices is lower than the load capacity of busbars that are exclusively serving for power distribution. The corresponding tables can be found in the annex to IEC 60890.

6.1.4.4 Conductor length

As shown in Section **6.1.2** in the type tests for devices comparatively long connecting lines to the terminals are used and these help to radiate a substantial amount of heat from the devices. With short connections this does not occur. As a consequence the temperatures of the terminals, the device interiors and the conductors themselves rise even if the load remains unchanged. For this reason, with compact device assemblies such as for example motor starters consisting of a circuit breaker and a contactor, type tests of the complete starter including the connecting (power wiring) components are performed. The power wiring modules have a higher temperature withstand than normal wiring material and the tests ensure that the temperature-rise limits for all the components are observed.

Fig. 6.1-5
With compact motor starters with power wiring modules, the type test ensures that the limit temperatures of all components are observed.

With short connections in individually wired installations, compliance with the temperature limits should be ensured by load reduction and/or forced cooling. The selection of larger connecting cross-sections increases the heat exchange of mutually connected devices and reduces the amount of heat dissipation in the conductor itself. Therefore the rate of heat-flow to the outside is not improved.

6.1.4.5 Tightening torques

In the catalogues and on the devices themselves, often ranges for the tightening torques of the terminals are stated. These then relate to all current ranges and the respective wire sizes for a frame size. From the point of view of device heating it is a good idea to always use a value in the upper part of the torque range as this will have a positive effect on the electrical and thermal transition resistance and hence the heat generation and flow. See **Fig. 6.1-6**. The upper range limit should not be exceeded so that the mechanical strength of the terminals is not unacceptably stressed.

6.1.4.6 Line ducting

As can be seen from the relevant tables (see also RALVET) for conductor selection, the method of installation (in the open, on tracks, in cable ducts etc.) and the accumulation of conductors have a large influence on their load-carrying capacity. The more heat-flow to the surrounding air is prevented, the lower is the load capacity or, in other words, the greater is the required cross-section for a given current. For technical reasons therefore, the lines should be laid as loosely as possible. Lines that are routed into a cable duct only a short distance from the connection terminal have a relative short open length over which heat can be dissipated and they mutually heat each other in the duct.

6.1.4.7 Operating frequency and harmonics

All normal technical data and tests relate to the normal supply frequency of 50/60 Hz. At higher frequencies additional losses occur that adversely affect the loss balance or reduce the load capacity of the devices. See Section **2.4.3**.

6.1.4.8 Mounting devices side-by-side

In real-life switchgear assemblies, the switchgear devices are very often placed in rows side-by-side. Circulation of the ambient air between the devices is then not possible and as a consequence the rate of cooling of devices in comparison to the standard test conditions is reduced (see **Fig. 6.1-5**). Where this results in an inadmissible temperature rise, then a reduction in load capacity will occur.

In practice, adjacent devices are frequently not loaded at the same time or the devices are operated with currents that are well below the conventional thermal current in open air (I_{th}). In such cases, adjacent placement of devices is permissible with respect to temperature-rise.

Care is required when operating adjacent devices close to the I_{th} and in case of a combination of adverse factors with respect to the heating as described above. In such cases, spacing between the devices is recommended in order to reduce mutual heating. Often instructions are included in the manufacturer's information – for example with the dimensional drawings (catalog, packaging, application recommendations). To avoid hotspots, circulation of the air in switchgear assemblies is advantageous.

6.1.4.9 Mounting position

In manufacturers documentation there are specifications with respect to the permissible mounting positions and in the case of installations differing from the normal positions the corresponding influence on the operational parameters. With respect to heating effects it should also be remembered that heat dissipation within the devices is not evenly distributed, but is concentrated on specific components, for example, the bimetal strips of circuit breakers or motor protection relays. With a mounting position that differs from normal, the mutual effect on adjacent devices can also change.

6.1.5 Thermal imaging cameras

Thermal imaging cameras are increasingly being used to examine heat formation in switchgear assemblies. They are a very useful tool for recognizing critical spots, but there is also a certain risk of incorrect interpretation of measurements. Thus an apparently high measured surface temperature can be caused by radiation from hot internal components, although in fact – for example when measured with thermocouples – the hot-spot is actually below the surface. Incorrect measurements are possible due to the different emission factors of the various materials used. It is a good idea to get the advice of a competent specialist if apparently excessive high temperatures are measured.

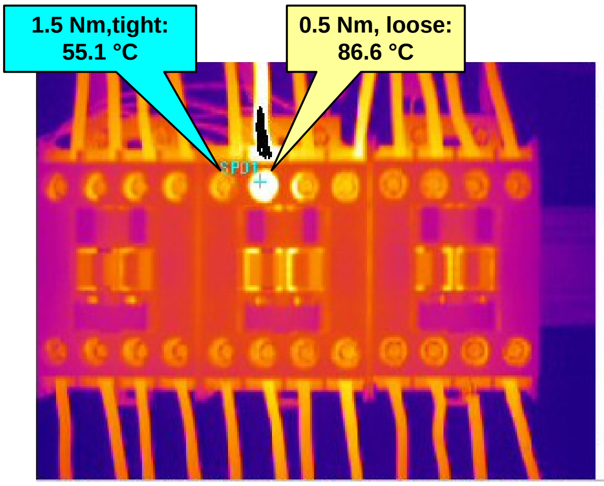

Fig. 6.1-6
Picture of a device made with a thermal imaging camera. Effect of the tightening torque on terminal heating. The various temperatures are represented with colors. At interpretation the emission factors of the various surfaces should be considered.

With thermal imaging cameras, the temperatures of the visible surfaces can be measured. Overheating on the inside of a device can manifest itself in the increased temperature of a visible surface. Thus a worn out main contact can show-up through an increase in visible surface-temperature on the associated terminal. However, by far the most common explanation of unexpectedly high temperature on a terminal is a loose connection.

It is useful to perform temperature-rise measurements at long intervals in order to determine changes and establish whether these changes are due to the devices, connections or with respect to some variation in their load.

6.2 Short-circuit withstand capacity

In accordance with IEC 60439-1 verification of the short-circuit withstand capacity of a switch-gear assembly is mandatory from a prospective short-circuit current of 10 kA_{eff} or 17 kA_{pk} (peak value) upwards. Below these limit values the withstand capacity is not stated, as the stress generated by the forces is not regarded as critical.

For auxiliary circuits that are connected to control transformers, the limits of 10 kVA at ≥ 110 V and 1.6 kVA at < 110 V at a minimum short-circuit voltage of 4 % apply. Below these values verification of the short-circuit withstand capacity is not required.

It is important to note that verification of the short-circuit withstand capacity is not required for components, where the short-circuit withstand capacity for the conditions under which they are used in the relevant switchgear assembly has been verified by type testing. Examples of these are: busbars, busbar supports, connections to bus-bars, input and output units, switchgear etc. In practice, this means that type-tested devices or subassemblies (for example contactors, motor starters, motor protective devices, bus-bar systems) can be used without further verification of their short-circuit withstand capacity, insofar as their type test includes loading in the given switchgear assembly.

If, for example, for a two-component motor starter consisting of a circuit breaker with motor protection characteristic and a contactor, there is a coordination table available for 400 V at a conditional rated short-circuit current I_q = 50 kA, then starters from this table can be used for all applications with $I_q \leq$ 50 kA without further verification of the short-circuit withstand capacity. Manufacturer instructions, where they exist, must be observed.

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[1)] IEC 60439-1 shall be replaced by IEC 61439-1 and IEC 61439-2

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