Electrical switching devices and insulators

BMEVIVEM173

Koller, László
Novák, Balázs
Tamus, Ádám
Electrical switching devices and insulators
irta Koller, László, Novák, Balázs, és Tamus, Ádám

Publication date 2012
Szerzői jog © 2011
Tartalom

Preface ................................................................................................................................. v
1. Introduction ....................................................................................................................... 1
2. Switching transients .......................................................................................................... 6
   1. Switch-on processes ...................................................................................................... 7
      1.1. Fault far from the generator ................................................................................ 7
      1.2. Switch-on of a transformer under no-load condition ........................................... 10
   2. The electric arc ............................................................................................................ 12
      2.1. V-I characteristics of the steady-state arc ........................................................... 13
      2.2. Dynamic arc characteristics ............................................................................... 14
         2.2.1. Arc characteristics in HV circuits ................................................................. 14
         2.2.2. Arc characteristics in LV circuits ................................................................ 15
         2.2.3. Arc quenching and re-ignition in a switching device ..................................... 15
   3. Switch-off processes .................................................................................................... 18
      3.1. Ideal interruption of an HV terminal fault ............................................................ 18
      3.2. Interruption of small inductive currents in HV circuits ......................................... 21
         3.2.1. Interruption without current limitation ......................................................... 23
         3.2.2. Interruption with current limitation ............................................................... 24
   3. Thermal transients ....................................................................................................... 26
      1. Slow temperature rise .............................................................................................. 28
      2. Fast (short-circuit) temperature rise ....................................................................... 29
      3. Permitted temperature rise ..................................................................................... 30
   4. Mechanical transients ................................................................................................ 32
      1. Force calculation based on Biot-Sawart law ............................................................ 33
      2. Force calculation based on the change of magnetic energy ................................. 34
      3. Direction of force .................................................................................................... 35
      4. Repulsive force in current constrictions .................................................................. 36
      5. Effect of electrical transients .................................................................................. 36
   5. General rules of switching device selection .................................................................. 38
   6. Structure and operation of electrical switching devices .............................................. 39
      1. Relays and releases .................................................................................................. 39
         1.1. Properties, classification ................................................................................... 40
         1.2. Electromagnetic relays and releases ................................................................... 41
         1.3. Magneto-mechanical relays ............................................................................... 43
         1.4. Thermo-mechanical relays ................................................................................ 43
            1.4.1. Bimetallic switch ......................................................................................... 43
            1.4.2. Thermistor relay ......................................................................................... 44
      2. Circuit breakers ......................................................................................................... 44
         2.1. High voltage circuit breakers ............................................................................. 45
         2.2. Low voltage circuit breaker ............................................................................... 48
            2.2.1. Structural elements .................................................................................... 49
            2.2.2. General purpose circuit breakers ............................................................... 50
            2.2.3. Current limiting circuit breakers ................................................................. 53
            2.2.4. Miniature circuit breakers (MCB) ................................................................. 55
            2.2.5. Selection .................................................................................................... 57
      3. Fuses .......................................................................................................................... 60
         3.1. Medium voltage fuses ....................................................................................... 61
            3.1.1. Short-circuit operation ............................................................................... 61
            3.1.2. Overload operation .................................................................................... 65
            3.1.3. Structure ..................................................................................................... 67
         3.2. Low voltage fuses .............................................................................................. 68
            3.2.1. Structure and properties ............................................................................ 68
            3.2.2. Operation during short-circuit ................................................................... 70
            3.2.3. Operation during overloads ....................................................................... 73
            3.2.4. Selection ..................................................................................................... 77
   4. Disconnectors ................................................................................................................ 78
Preface

This electronic book covers the topics of a university subject having the same title, and in which the Faculty of Electrical Engineering and Informatics of the Budapest University of Technology and Economics offers MSc courses. According to its title, the book presents two, highly related technical fields. Five chapters deal with electrical switching devices and three with insulation technology. The first, introductory chapter defines some essential concepts necessary for understanding the remaining of the book.

Electrical devices do not generate, distribute or measure electric power. Among the electric power consuming equipment, we do not consider the motors, and lighting units as electrical devices. However, the range of electrical devices is still very wide, and we deal only with electrical switching devices.

The students of MSc subjects must have a basic knowledge of the field from their previous BSc studies. Considering that there is no sharp boundary between the bachelor and master courses, this book discusses those parts of the BSc subject, which are highly relevant for conceiving the new material.

The different courses, subjects, and topics have continuously changed and developed during the years of their existence. This entailed the publication of several different lecture notes related to each other. The contents of the current book are based on the lecture notes published in [1–3]. Although these three books cover a wide range of related topics about electrical switching devices and equipment, their structure does not provide an easy overview of the field. We tried to fulfill the need for a clear overview by restructuring and rewriting the existing material. We complemented the previous text with new chapters, and added new summaries and explanations. However, because of size limits, we had to omit some special or less up-to-date topics. To make comprehension easier, we redrew most of the figures in colors, and in one case, we attached an animated drawing.

We hope that the students will be able to use our electronic lecture notes effectively during their studies.

Budapest, September 2011.
1. fejezet - Introduction

The main purpose of electrical switching devices is to turn on or off electrical circuits, and to provide a path for the current during their on state. They are of greatest importance in 50 or 60 Hz electric power systems. Not only do they make the transmission of electric power possible, but their failure can lead to losses – due to the interruption of power distribution, or the damage of valuable equipment – much-much higher than their own value. Therefore, electrical switching devices must be reliable, and owing to their high number in electric power systems, their manufacturing must be cost effective. To achieve efficient transmission of electric power, different voltage levels are utilized in power systems. Higher the transmitted power or longer the distance of transmission, higher is the rated voltage of the system (V$_r$=0.4; 10; 20; 35; 120; 220; 400; 750 kV). Obviously, the rated voltage of the electrical switching devices has to exceed that of the network, in which they are installed. Consequently the rated voltages of high voltage equipment are 12, 24, 40.5, 145, 245, 420 and 787 kV respectively. Similar to the electrical grid, the switching devices can be classified as “low”, “medium”, “high”, “very high” and “ultra high” voltage types (Fig. 1.1). However, the more simple classification of low voltage (LV; <0.4 kV), medium voltage (MV; 12, 24, 40.5 kV) and high voltage (HV; 145, 245, 420 and 787 kV) is more general.

Electrical switching devices are rarely standalone units, usually several of them are installed together at specific points of the electrical systems, forming – together with connecting elements – switchgears. Switchgear is a general term covering switching devices and their combination with associated control, measuring, protective and regulating equipment, also assemblies of such devices and equipment with associated interconnections, accessories, enclosures and supporting structures.

Besides their rated voltage, electrical switching devices must be appropriately selected according to their purpose and function. In accordance with this function, first we have to discuss the normal operating, rated, overload, and fault (short-circuit) currents occurring in normal and faulty states of the electrical systems. These system states can be made or terminated by electrical switching devices, but they can be caused unintentionally by faults (short-circuit or disruption) as well.

Turning on or off consumer loads corresponds to the normal operation of three-phase systems. Although sometimes, the elements of electric power systems have to make switching operations during no-load conditions too (e.g. turning on/off a transformer or transmission line which is not in use).

Switching operations can occur in a faulty state of the system as well, like during overloads or short-circuits. For instance, turning on a faulty equipment can result in making a short-circuit current. The electrical switching devices are responsible for the automatic disconnection (interruption) of this excessive current.

We discuss the characteristic currents of the different system states by means of simplified single-phase models of the symmetrical three-phase systems.
Fig. 1.2. Normal condition

Figure 1.2 shows the one-line equivalent circuit of the electric power system during normal conditions. The reactance and impedance of an inductive operating load having inductance \( L \) and resistance \( R \) per phase:

\[
X = \omega \cdot L; \quad Z = \sqrt{R^2 + X^2},
\]

(1-1)

where, in case of frequency \( f \), the angular frequency:

\[
\omega = 2 \cdot \pi \cdot f.
\]

Modeling the network between the switching device \( K \) and the generator having \( V_p \) phase voltage by an inductance \( L_m \) and a resistance \( R_m \), the reactance and impedance of the connecting network:

\[
X_m = \omega \cdot L_m; \quad Z_m = \sqrt{R_m^2 + X_m^2},
\]

(1-2)

To achieve economic power supply, the rate between the elements of the connection link and the load should be kept such, to make the load impedance and the resultant impedance \( Z \), of the network almost equal:

\[
Z_r = \sqrt{(R_m + R)^2 + (X_m + X)^2} \approx Z,
\]

(1-3)

and as a consequence:

\[
Z_m \ll Z.
\]

(1-4)

Consequently, the operating current \( I_o \) flowing through the load and the serial elements of the connection:

\[
I_o = \frac{V_p}{Z}.
\]

(1-5)

The operating current must not exceed the rated current \( I_r \), since the serial elements of the network cannot withstand a higher current without detrimental overheating. The smallest load impedance corresponding to \( I_r \):

\[
Z_p = \frac{V_p}{I_r}.
\]

(1-6)

Fig. 1.3. Overload condition

In Fig. 1.3, the equivalent circuit representing a fault (overload) condition of the system can be derived from the previous case of normal operation by inserting a load impedance \( Z \) parallel to the rated load impedance \( Z_r \). Since in this case

\[
Z_{ol} \ll Z_r \quad I_{ol} = \frac{V_p}{Z_{ol}} > I_r,
\]

(1-7)
A steadily flowing overload current can lead to the overheating of the serial network elements, therefore protective measures have to be taken to disconnect overloads. However, disconnection should be accomplished only if the temperature rise reaches an allowed level. Overload currents can belong to the normal behavior of the electrical systems – like inrush currents of electrical motors – and their instant interruption would block the operation of devices producing them.

In Fig. 1.4 a fault (short-circuit) condition occurred during normal operation in the electrical system. The impedance $Z$ of the load is shunted by a short-circuit impedance of zero value in the equivalent circuit.

$$I_{sc} = \frac{V_p}{Z_m} \gg I_0$$

The huge short circuit current would damage the electrical equipment in a very short time, therefore it must be interrupted instantly or (possibly without a delay) as fast as possible.

After describing the rated voltages and the different states and current levels of the electrical systems, we introduce the reader to the different types of electrical switching devices used in electric power transmission and distribution. The switch $K$ in the previous figures (1.2 … 1.4) can be substituted by these switching devices having different functions and purposes. We provide detailed descriptions later in chapter 6, which discusses the construction and operation of electrical switching devices.

1. **The high, medium, and low voltage circuit breakers** (CB) are mechanical switching devices that can make or break currents during normal or fault (including short-circuit) conditions. Mechanical means that switching operation is accomplished by separable opening or closing contacts. Furthermore, if their contacts are closed, CBs have to be able to conduct operating currents for an unlimited and fault currents for a limited time.

2. **The low and medium voltage fuses** are electrical switching devices that automatically interrupt excessive currents lasting for a specific time by melting one or more metal wires or strips connected parallel (fuse element) inside a fuse link and quenching the electric arc, which occurs after melting. The fuse element has a relatively small cross sectional area, thus it can be considered as an intentionally weakened point of the electrical network. The fuse has two functions: first of all it provides protection against short circuits and limited protection against overload currents. It has to be able to conduct rated or less than rated currents for an unlimited time. Consequently, the function of the fuse is similar to that of the CB, but providing interruption only once. It is a protective device in the electric power system.

3. **The high and medium voltage disconnectors or isolators** are mechanical switching devices, which provide complete insulation distance called isolation distance between their open contacts. They have to satisfy safety and electrical requirements regarding their open contacts that is, as their major task, they have to provide safe and visible separation between parts of the electrical system. They have negligible current interrupting capability and are only used in the off-load condition. They can be operated only if negligible current flows through them, or if the voltage across their contacts is insignificant. If their contacts are closed, they have to be able to conduct rated current for unlimited time and they have to withstand the thermal and dynamic effects of short-circuit currents. Their secondary task is to arrange the path of the current. An example is a double busbar system, where disconnectors provide the way for the power flow between the busbars. Disconnectors are often equipped with earthing switches or earthing knives.

4. **The medium and low voltage (mechanical or semiconductor) load break switches** can make or break currents during normal, operating conditions. These include some specific overload conditions as well. Furthermore, they have to be able to conduct currents different from normal conditions (faults) until the
protective measures are taken. The mechanical contactor is a special load break switch. An electromagnet provides the driving force to close its contacts; therefore it has a special construction and tasks. The semiconductor switches form a separate group of load break switches. By controlling the conductivity of semiconductor elements in them, they can turn on or off electrical circuits. They can be used also for similar tasks as the contactors.

5. Owing to their smaller size, easier installation and favorable price, medium and low voltage combinations of switching devices providing the tasks of two or three basic units are used mostly in indoor applications. They can be classified in two groups:

The manufacturer assembles serial connected switching devices in a single unit. This does not really result in new device types, only the on-site installation work becomes simpler. The basic switching devices can be easily recognized in these units (e.g. disconnector-fuse, switch-fuse, switch-disconnector-fuse, integrally fused circuit-breaker).

New constructions made from basic switching devices (e.g. fuse-switch, fuse-disconnector, fuse-switch-disconnector).

1. High and low voltage overvoltage protective devices (spark gap, surge arrester, varistor, etc.) play a crucial role in electric power systems, although they are not serial elements. Their task is to limit the level of overvoltages in an electrical network. During most of their operating time they remain idle, they do not contribute to the operation of the system. They cannot be activated directly or intentionally, although overvoltages in the system or in the equipment automatically trigger their operation.

2. Automatic protection relays and releases provide safety and improve the reliability of the transmission, distribution and consumer electrical systems. The protection relays and releases can be standalone units, or replaceable or fixed elements of other switching devices (e.g. CB), or they can provide auxiliary protective functions (e.g. with contactors). Their task is to continuously monitor different parameters of electrical systems or equipment. Based on the variation of these parameters they detect faults or other abnormal conditions, enable fault clearance, terminate abnormal conditions, and initiate signals or indications automatically without human interaction.

![Diagram](image)

Fig. 1.5. MV/LV transformer substation

Substations and transformer stations are situated at the connection points of power transmission or distribution lines in the power system. The incoming and outgoing lines are connected to busbars by means of electrical switching devices. As an example, Fig. 1.5 depicts the simplified one-line diagram of one fraction of an industrial MV/LV transformer substation. An underground cable supplies power to the single busbar substation through a disconnector with an earthing knife (DE). The fault protection of the cable is accomplished by a circuit breaker in the substation at the supply side of the cable. One of the MV motor circuits is protected and switched by a withdrawable circuit breaker (CB), whereas the other by a withdrawable switch-fuse. Besides the CB protected motor circuit connection, the MV switchgear includes the connection for the MV/LV transformer.
with a disconnector and a fuse. The secondary side of the transformer is connected to the low voltage busbar through a circuit breaker. The first bay of the low voltage side supplies a motor circuit through a fuse (F) and protective thermal relay (Th). The second bay supplies a lighting circuit through a load break switch (SW) and a fuse. A disconnector-fuse is installed in the third, whereas a switch-fuse in the fourth low voltage bay of the substation.
2. fejezet - Switching transients

Switch on and off operations induce energy change in an electric power system, therefore electric transients – and between the separated contacts of mechanical switching devices, the effects of electric arc – have to be taken into account until the network reaches quasi steady-state. The transients and the arc can temporarily have adverse effects, as they increase the electrical, mechanical and thermal stresses of the power system. Since switching devices are part of the system, their operation is also influenced by these effects.

In the circuit representing a fault condition in Fig. 1.4, let the switch $K$ model the contacts of a real switching device (e.g. CB). Figure 2.1 illustrates the steps of its operation during making and breaking a fault current. While the contacts are open (1), no current is flowing in the circuit ($i=0$). During a closing operation, before the contact members reach each other, a sparkover occurs initiating an electric arc. A fault current of $i=i_{sc}$ flows through the arc (2). However, this arc can occur only on high voltages and its duration is very short, since it extinguishes after the contacts get closed. At this moment, a prospective short circuit current $i=i_{sc}$ starts to flow through the contact members (3). This short circuit current would be harmful for the system; therefore a protective relay automatically triggers the CB to interrupt it. After the protection trips the CB, the contact members start to separate and – both on LV and HV – an electric arc starts burning between them (4). The constriction of the current to small spots on the contact surfaces explains the fact that there is always an arc between the opening contact members during current interruption. During opening, the number and the area of the contacting spots rapidly decreases, making the current density so high at some points that its heat melts and vaporize the surface. The ionized metal vapor provides a conducting path for the arc. If the arc was a perfect conductor, in a circuit with sinusoidal supply voltage, the prospective short circuit current $i_{sc}$ would continuously flow at least until its first current zero. In reality however, the electric arc is a non-linear, resistive element of the circuit, and the dynamic arc of an AC circuit makes the current $i=i_{sc}$ distorted that is non-sinusoidal. This current lasts at least until its first current zero. The interruption is successful, if the arc finally extinguishes, or more precisely, if re-ignition of the arc can be inhibited at or close to the current zero. If re-ignition happens, $i_{sc}$ further flows up to its next current zero. The moment of the current zero and also the highest value of the arc current are both influenced by the shape and magnitude of the arc voltage. In HV circuits, the voltage of the relatively low resistance arc is negligible compared to the supply voltage: the arc modifies the current time function only close to current zero. The situation is different in LV circuits, where the arc has relatively high resistance, and its voltage is comparable to – sometimes its momentary value is even higher than that of – the supply voltage. In this case, the arc current significantly differs from the arc-free prospective current. Both the peak and the moments of current zeros of the arc current and the prospective current can be different. This difference is the most pronounced with current limiting circuit breakers. The contact members of these devices are separating so fast and the arc voltage is increasing above the momentary value of the supply voltage so rapidly that the peak of the arc current (let-through current) becomes significantly less than the peak of the prospective current. Fuses limit the current similarly, although in their case the melting of the fuse element corresponds to the contact separation of circuit breakers. The fault current in DC circuits can be interrupted that is, current zero can occur only, if the arc voltage between the contacts exceeds the DC supply voltage. Even current limitation is possible in this case, if the contacts separate before reaching the steady-state fault current.

The interruption is successful (5), if the arc finally quenches, namely it cannot re-ignite. This results in the initial state (1) of the switching device in Fig. 2.1. A transient recovery voltage (TRV) appearing between the contact members after a current zero can cause dielectric or thermal re-ignition of the arc. The time function of the TRV is determined by the elements of the circuit (resistances, inductances, capacitances) and the resistance of the electric arc.

$\begin{align*}
&i=0 \\
&i=i_{arc} \\
&i=i_{arc} \\
&i=i_{arc} \\
&i=0
\end{align*}$

Fig. 2.1. Operating states of the contacts of an electric switching device

We use the electrical switching devices mostly in three-phase AC power transmission and distribution systems. Therefore, by operating them, we modify the operating state of these systems (even if we just turn on a lamp in a room with a single-pole switch). Furthermore, the switching operations are often asymmetric, the network parameters are distributed and the elements of the network are non-linear (e.g. the electric arc). Precise modeling of such complex processes would be very complicated, therefore we use simplified models to explain and demonstrate the nature of switching processes. Unfortunately, the simplest non-linear, single-phase,
Switching transients

A concentrated parameter model including an “ideal” switch (having infinite resistance in its open and zero resistance in its closed position) is not always appropriate to describe the electric transients caused by switching operations. In some of the cases, we have to take into account the effects of the non-linear arc between the contact members of the switching device.

We have seen that the operation method of the switching devices can differ on different voltage levels. Furthermore, at low voltages, even the current type is an important influencing factor. The voltage level determines the values and rates of network parameters (e.g., power factor) as well. Consequently, it is essential to classify also the electric transients according to voltage and – at low voltages – according to current type. There are situations, where these classifications are not relevant, since the given physical process can happen both at low and high voltages. We note here that, because of the limited size of this book, we discuss only AC phenomena more typical in practice. We will follow the operating states shown in Fig. 2.1 during our discussion. First we treat the switch-on transients, second the properties of the electric arc between the contacts, and finally the processes taking place during switch-off operations. We discuss the electric transients caused by fuses together with the structure and operation of the electric switching devices in another chapter.

1. Switch-on processes

In AC circuits, the supply voltage affects the switch-on processes only through the parameters of the circuit elements; therefore we do not distinguish switch-on processes regarding the voltage level.

In Fig. 1.2, we have seen that the equivalent circuit must include a resistance and an inductance representing the three-phase synchronous generator. Due to the increase of current during a short circuit, the values of the generator parameters – especially the inductance – significantly change. In most of the practical cases, we neglect this change, since constant inductances and other constant elements – representing the transformers, transmission lines, etc. – with much higher values than that of the generator’s are connected in series with the generator. We can say that a circuit with constant parameters represents a fault far from the generator. We discuss this fault type and the electric transients caused by switching on of a load-free transformer in the followings.

1.1. Fault far from the generator

Figure 2.2.a shows the equivalent circuit modeling a fault current switch-on. The lumped resistance and inductance \( R \) and \( L \) represent the generator, lines, transformer, etc. together. Furthermore, \( v = V_m \cdot \cos \omega t \) is the momentary value of the supply voltage. The switching device is in open position, current has not been flowing in the circuit, and thus the inductance is energy-free. The fault occurs and a current starts to flow, when the switch is turned on at the moment of \( t = 0 \). The time function \( i(t) \) of this current depends not only on the phase angle \( \phi \), but also on the moment of fault occurrence.

The fault current reaches steady-state after a long time, the maximum of its momentary value:

\[
I_m = \frac{V_m}{Z},
\]

(2-1)

where

\[ Z = \sqrt{R^2 + \omega^2 L^2}. \]

The steady-state current lags behind the supply voltage by an angle of

\[ \phi = \arctan \frac{\omega L}{R}, \]

therefore its time function:

\[
i_{st}(t) = I_m \cdot \cos(\omega t \cdot \phi).
\]

(2-2)
Figure 2.2.b shows this time function together with the supply voltage, with $\omega t/\pi$ on the horizontal axis of the diagram. The fault can randomly occur in any moment. If the fault occurs exactly at the moment of a steady-state current zero, then the steady-state current will start to flow immediately. In this case, the time-function of the fault current coincides with that of the steady-state current: $i(t)=i_{st}(t)$. The zero steady-state current at the moment of switch-on ensures that the inductance is energy-free in this favorable case. In any other case, the steady-state current differs from zero at the moment of switch-on. Since the inductance must be energy-free, a transient current component $i_{tr}$ compensating this finite current appears in the system. Therefore the time-function of the fault current in a general case:

$$i(t) = i_{st}(t) + i_{tr}(t).$$

(2.3)

The moment of switch-on, $t=0$ determining $i_{st}(0)$ is indicated by the vertical axis for a general case. This moment is shifted by a $\psi$ switch-on angle in the positive direction from the positive crest of $v$. Since no current has been flowing before $t=0$, and because the current cannot jump in a circuit including an inductance, current cannot flow either at the moment of $t=0$. Therefore

$$i(0) = 0 = i_{st}(0) + i_{tr}(0),$$

from which the initial value of the transient component:

$$i_{tr}(0) = -i_{st}(0).$$

The initial magnitude of the transient current equals to that of the steady-state current, but with opposite sign. The transient current exponentially decreases from this initial value and tends to zero after a long time. The ohmic resistance of the circuit results in the damping in the system. The transient component is plotted in Fig. 2.2.c, considering that

$$i_{tr}(t) = i_{tr}(0) \cdot e^{\frac{-t}{T}},$$

(2.4)

where

$$T = \frac{L}{R},$$

(2.5)

is the time constant of the circuit.
The sum of $i_{st}(t)$ and $i_{tr}(t)$ results in the time-function of the fault current $i(t)$ that we wanted to determine:

$$i(t) = I_m \cdot \left[ \cos(\omega t + \psi - \varphi) - \cos(\psi - \varphi) \cdot e^{\frac{t}{T}} \right].$$

(2-6)

This current, together with its two components, is plotted in Fig. 2.2.d. It can be clearly seen that its peak is higher than $I_m$.

The initial value of the transient current $i_{tr}(0)$ and consequently the peak of the resultant current depends on the moment of current initiation. In a circuit with phase angle $\varphi$, this moment is determined by the switch-on angle $\psi$. The most unfortunate time instant of current initiation generates the possible highest peak $(I^*_{tr})$. In any inductive circuit, this time instant belongs to $\psi=\pm\pi/2$ that is, when the current starts exactly at the moment of supply voltage zero (see Fig. 2.3). In a solely inductive circuit $(\varphi=\pi/2)$, the peak factor

$$k_p = \frac{I^*_{tr}}{I_m}$$
Switching transients

(2-7)

is \( k_p = 2 \). Nevertheless, there is always a resistive component in a real circuit, therefore, when calculating the effects of the current, an average value of \( k_p = 1.8 \) is acceptable.

Figure 2.4 shows the “favorable” situation mentioned before \((\psi - \varphi/\pi)\), when transient does not take place, leading to a peak factor of \( k_p = 1 \). Figure 2.5 depicts another special example, when the transient starts from its possible highest value, namely when the current was initiated at the steady-state current peak \((\psi - \varphi = 0)\). In this case, the possible maximum of the resultant current is less than – in solely inductive circuits equal to \(-I_m\) corresponding to a switch-on at voltage zero.

![Fig. 2.4. No transient component](image)

![Fig. 2.5. Possible highest transient](image)

1.2. Switch-on of a transformer under no-load condition

Although the steady-state no-load current of a transformer is much less than its rated current, switching on a load free transformer can cause a transient that can reach even 100 times the steady-state for a short time. This in-rush current is so high that it can amount to several times of the rated current.

![Fig. 2.6. Equivalent circuit](image)

To understand this adverse phenomenon, let us consider the circuit of Fig. 2.6, where \( \Psi(i) \) represents the magnetic flux of the transformer, as a non-linear function of its current. Applying Kirchoff’s II. law to the circuit:

\[
V_n \cdot \cos(\omega t + \psi) = \frac{d\Psi(i)}{dt} + R \cdot i(t),
\]

(2-8)

where \( \psi \) is the switch-on angle.

To solve the differential equation, we have to know the non-linear relation \( \psi(i) \) that is, the magnetization curve \( B-H \) of the transformer. The hysteresis of the magnetization curve makes the problem even more complicated.
Nonetheless, the hysteresis loop approaches the shape of the quasi steady-state curve only after the transients has been subsided. As a simplification, we neglect the resistance of the circuit ($R=0$), and after applying the boundary conditions, we solve the problem by a graphical method. First we plot the time-function of the magnetic flux, which – together with the magnetization curve – yields the time variation of the current.

The sinusoidal steady-state flux $\Psi_{st}(i)$ lags behind the sinusoidal supply voltage by an angle of $\pi/2$. If we know the hysteresis curve $\Psi(i)_s$, valid in steady-state, from the flux we can plot the distorted steady-state current point by point. This current is the no-load current of the transformer (Fig. 2.7).

Fig. 2.7. Obtaining the load-free steady-state current

To begin with, we assume that the transformer’s yoke did not have any remanent flux at the moment of switch-on ($\Psi(0)=0$), but the switch-on occurred at the worst time instant, namely at voltage zero. This time instant corresponds to the angle of $\varphi=-\pi/2$. Figure 2.8 depicts the resultant flux $\Psi(t)$ in this case. In reality however, there is always a remanent flux in the yoke of a previously used transformer. This remanent flux can be positive or negative. In our case, the positive value results in higher initial flux and therefore in higher surge current. By adding $\Psi_r$ to $\Psi(t)$, we can obtain the flux $\Psi_{init}(t)$ valid at the beginning of the switching process.

Fig. 2.8. Obtaining $\Psi(t)$, if $\Psi_r=0$

To obtain the time function $i(t)_{init}$ of the initial current, we have to know the initial flux curves $\Psi(i)_{init}$ originating at the corners of the hysteresis loops as well. Like in Fig. 2.9, the first section of these curves can be approximated by a straight line starting from the point of the positive remanent flux ($\Psi_r$). Together with the initial flux $\Psi_{init}(t)$, this low steepness line yields the time function of the initial current $i_{init}(t)$, as it can be seen in Fig. 2.10. In short, the causes of the initial large current surges are the following: switch-on at voltage zero, the remanent flux, and the low steepness of the magnetization curve.
Fig. 2.9. Obtaining $\Psi_{\text{init}}(t)$ and $\Psi(t)_{\text{init}}$

Table 2.1 demonstrates for different – core- and shell-types of – transformers that, depending on the rated power ($S$) of the transformer, the maximum of the no-load initial current surge ($I_{\text{min}}$) can significantly exceed the peak of the rated current ($I_{\text{mr}}$). The ratio $I_{\text{min}}/I_{\text{mr}}$ is higher with core-type – where the flux lines are connected with each other – than with shell-type of transformers.

Table 2.1

<table>
<thead>
<tr>
<th>$S$ [MVA]</th>
<th>core-type</th>
<th>shell-type</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>3</td>
<td>2</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>.</td>
<td>.</td>
<td>.</td>
</tr>
<tr>
<td>20</td>
<td>8</td>
<td>5</td>
</tr>
</tbody>
</table>

2. The electric arc
The electric arc is a type of gas discharge, in which the current intensity is typically higher than 1 A. Therefore thermal ionization processes play a much more significant role in generating and maintaining the arc, and determining its main characteristics than electric ionization processes.

Fig. 2.11. Voltage distribution along the arc length

The electric arc consists of ionized gas, and it originates and ends on small spots on the electrodes. The spot moves in a rapid and irregular way on the cathode. The spatial stability of this movement depends on the cathode material. Materials with high melting temperatures (e.g. wolfram) ensure high cathode temperatures, resulting in a relatively stable arc. The electric potential distribution along the arc is plotted against the arc length in Fig. 2.11. In the vicinity of the anode and the cathode, charge carriers with opposite sign to that of the electrodes are generated. There are three distinct regions of an electric arc, namely the cathode drop region, the arc column or arc plasma region and the anode drop region. The cathode is negative, the anode is positive and the arc column – situated in between anode and cathode drop regions – is electrically neutral, as it contains equal number of ions and electrons. The length of the anode and cathode drop regions (\(l_a\) and \(l_c\)) is small; it is of the order of micrometers, and \(l_a \ll l_c\). It can be seen that the electric field strength is much higher in these regions than in the arc column. If the arc length is short, the voltage along the arc column becomes negligible, the arc voltage is determined by the anode and cathode drops (in an extreme case, with zero arc length, only the latter two contribute to the arc voltage). Arcs burning between the mechanical contacts or between the deion plates of LV switching devices can be considered „short”. Therefore, the physical processes close to the anode and the cathode explain the behavior of such arcs in LV circuits. The properties of “long” arcs between the mechanical contacts of HV switching devices are mostly determined by the physical processes in the arc column.

This chapter summarizes only those properties of the switch arc, which help us to understand how the arc influences the switching processes in electrical circuits.

We say that the arc is steady-state, if the momentary value of the current flowing through it is constant. If this condition is not satisfied, the arc is dynamic, or, in the case of periodically varying current, the arc is quasi steady-state. It is worthy of notice that the arc is always dynamic in a switching device, since the current continuously changes during the switch-off process. The steady-state arc is a non-linear circuit element, its resistance is not a constant value; a characteristic curve represents the relation between its current and voltage. First we will introduce the steady-state arc characteristics, and based on it, we continue with the characteristics of the dynamic arc, discuss its properties in LV and HV circuits and its behavior during quenching and reignition.

2.1. \(V-I\) characteristics of the steady-state arc

The diagrams in Fig. 2.12 show arc characteristics at constant pressure (\(p=const\)) with different arc lengths (\(l_1 \leq l_2\)). It can be clearly seen that until about 1000 A the steepness of the curves is negative, indicating that larger current results in lower arc voltage. After a roughly horizontal section, further increase of the current above 10000 A goes together with rising arc voltage. This effect may be explained by the electrodynamic forces, which reduce the cross section of the arc channel (current filaments of the same direction attract each other).
2.2. Dynamic arc characteristics

If a time varying current \((\frac{di}{dt} \neq 0)\) flows through the arc, it can be modeled by dynamic characteristics. By starting from a single point of the steady-state \(V-I\) curve, and increasing the current at a finite rate \(\frac{di}{dt} \neq 0\) from \(i_1\) to \(i_2\), the voltage of the arc falls above the steady-state diagram. After getting to \(i_2\) the arc voltage needs some time to reach its steady-state value corresponding to \(i_2\) (Fig. 2.13). The phenomenon may be explained by the thermal inertia of the arc. In other words, the temperature and conductivity of the arc cannot follow the change of its current instantly; it tries to keep its conductivity belonging to \(i_1\). Similarly, if we reduce the current from \(i_2\) to \(i_1\) by the rate of \(\frac{di}{dt} < 0\), the voltage values fall below the steady-state characteristic curve. Theoretically, during an abrupt current jump \((\frac{di}{dt} = \infty)\) the conductivity could not follow the change of the current at all, the arc would become a linear element, Ohm’s law would be valid, and the resistance of the arc \(R_{arc}\) would become constant. The transient behavior and the thermal inertia of the arc can be represented by a thermal time constant \(\tau_{arc}\). Its value is in the order of \(10^{-6}\) to \(10^{-3}\) s, the lower limit typical in HV circuit breakers, whereas the higher one in air at atmospheric pressure.

2.2.1. Arc characteristics in HV circuits

With AC supply voltage, the current flowing through the arc is time varying, and quasi steady-state characteristics are valid. These characteristics depend on the values of the circuit elements as well. During switching off an HV circuit, the arc can be considered quasi steady-state, since the current can last up to several half cycles, and as the supply voltage is much higher than the arc voltage, the current hardly differs from sinusoidal. The diagrams in Fig. 2.14 show quasi steady-state arc current and voltage time-functions, together with the characteristic curve representing the relation between them. These diagrams are based on measurements and theoretical deductions valid for relatively long arcs. The corresponding current and voltage values follow a hysteresis loop. The polarities of the arc current and voltage are the same at every moment, and their zeros occur always at the same time. This means that the AC arc extinguishes before and re-ignites after every current zero. Peaks \((V_{ign} \text{ and } V_{qe})\), typical for extinction and re-ignition, can be easily recognized in the voltage time-functions at these time instants.
2.2.2. Arc characteristics in LV circuits

The voltage of a short arc in an LV circuit is comparable to, or sometimes is even higher than the supply voltage. Consequently, the time-function of the prospective current significantly changes after initiation of the arc. For instance the non-linear arc results in a distorted current in an AC circuit. The anode and cathode drops form a major part of the arc voltage, what is even more pronounced, when several short (0.3…1.0 mm) arcs are connected in series, each contributing to the voltage with its own anode and cathode drops. Therefore, the well-tried theories of long HV arcs are not valid in LV circuits. The time-function $v_{\text{arc}}(t)$ of the arc voltage in an LV switching device majorly differs from the quasi steady-state shape of Fig. 2.14 appearing in an HV unit. For instance, it does not have any well recognizable extinction and re-ignition peaks. The arc extinguishing mechanism of a switching device and the separation speed of the contacts determines this time function, and – according to measurements – its mathematical representation is rather simple:

$$v_{\text{arc}}(t) = V_{AK} + m \cdot t,$$

(2-9)

where $t$ is the time passed since the initiation of the arc (in case of mechanical contacts, the time from contact separation). Knowledge of this voltage and the parameters of the DC or AC low voltage circuit, makes possible to calculate the current $i(t)$ flowing through the arc.

2.2.3. Arc quenching and re-ignition in a switching device

The arc disappears if its current becomes zero. In case of DC interruption, the switching device itself must provide this condition by modifying the arc properties. With AC supply, the arc disappears at a natural current zero in HV circuits, or at a current zero determined by the arc voltage in an LV circuit. Another possibility is that the arc becomes unstable, and disappears shortly before these current zeros, resulting in a sudden drop of the current. This is the case of current chopping. If the switching device is capable of preventing the re-ignition, the arc eventually quenches, the interruption is successful. If re-ignition cannot be inhibited, the arc appears again and – in case of AC circuits – remains until the next current zero.

After current zero, an ionized channel called post-arc remains at the place of the arc. Only de-ionizing processes take place in this channel and the arc eventually quenches, if current does not flow for a prolonged period, and if
there is no electric field strength between the electrodes. Re-ignition can occur, if ionization surpasses de-ionization.

a) The arc can re-ignite in a gas if:

1. the recovery voltage (TRV) between the contacts generates a post-current or remanent current through the post-arc, and this current affects the thermal equilibrium of the post-arc such, that the heat content (and temperature) of the arc increases: \( \frac{dQ}{dt} > 0 \) (thermal re-ignition),

2. or the thermal processes are negligible (interrupting low currents at high voltage; or at low voltage, where the electrodes cool the arc), and fast increasing TRV results in collision ionization, which generates a re-strike (spark breakdown or dielectric re-ignition).

![Fig. 2.15. Time-function of re-strike voltage of a LV arc burning in air](image)

At low voltages, the electrodes have a relatively high mass, which results in powerful cooling and de-ionization of the arc burning in air. Therefore in LV equipment, the typical re-ignition is spark breakdown. To decide if the interruption can be successful, we have to know the time variation of the returning dielectric strength or breakdown voltage \( V_{\text{ign}} \) of the gas between the electrodes. A typical example of this re-strike voltage is illustrated in Fig. 2.15. The voltage \( V_{\text{ign}} \) reaches a \( V_{\text{ign0}} \) value in a very short time (1...3 μs) as the space charge in front of the cathode is neutralized rapidly. Higher the arc current, lower this \( V_{\text{ign0}} \), since stronger current generates more charge carriers before it reaches its zero. The value of \( V_{\text{ign0}} \) can be in the order of 160...210 V, when interrupting low currents (\( I < 100 \) A). This voltage is commensurable with the supply voltage. Although if the current exceeds 1000 A, it is much less, \( V_{\text{ign0}} \approx 10 \) V. The second, low gradient \( (k) \) region of the re-strike voltage corresponds to the neutralization of the arc column. The formula

\[
V_{\text{ign}} = V_{\text{ign0}} + k \cdot t
\]

(2-10)

provides a good approximation of the re-strike voltage time-function. As a consequence, the arc extinguishing methods in LV equipment are mostly based on increasing \( V_{\text{ign0}} \). This can be accomplished by multiplying the number of electrode gaps (more contact pairs in series) or by splitting the arc into small pieces (deion plates).

At high voltages, depending on the current to be interrupted, both thermal and dielectric re-strikes can occur. Fig. 2.16 shows the time-function of the re-strike voltage \( V_{\text{ign}} \) valid for both mechanisms. During calculations, we have to take into account the lower voltage values. For instance, with the current of \( I_1 \), the thick line provides the time-variation of the re-strike voltage. The curve corresponding to dielectric re-ignition can be approximated by formula (2-10) in this case as well.
Switching transients

Fig. 2.16. Time-functions of re-strike voltage of a HV arc burning in gas

Arc quenching methods based on the increase of $V_{\text{ign0}}$ with multiplied contact points or with deion plates can be feasible only up to some kilovolts, as costs and size quickly rise above a certain voltage. Considering the time-function of the dielectric re-strike voltage, the fast increase of the distance between the contact members and more pressure can raise the gradient $k$ of the recovering dielectric strength. The mechanism of thermal re-strike must also be considered. The HV switching devices have to accomplish two tasks to inhibit arc re-ignition. One of them is to reduce the arc energy

$$W_{\text{arc}} = \int_0^{t_{\text{arc}}} v_{\text{arc}} \cdot i_{\text{arc}} \cdot dt$$

(2-11)

before the current zero, namely before the arc annihilates. The other one is to promote de-ionization processes in the post-arc. Sometimes these aims conflict each other; for instance, cooling helps the de-ionization, but at the same time it increases the arc energy.

The general methods of arc quenching (preventing of re-strike) in gases at high voltage can be summarized as follows:

- raising the pressure (breakdown strength increases, number of ions is reduced),
- applying quenching material and cooling (helps de-ionization processes),
- removing ions by forced flow of the gas,
- lengthening the arc, increasing the electrode distance (breakdown strength increases).

Fig. 2.17. Equivalent circuit of a CB terminal fault

Smaller arc time constant $\tau_{\text{arc}}$ impedes both the thermal and the dielectric re-strikes more effectively. However, over-reducing $\tau_{\text{arc}}$ – e.g., by powerful cooling, namely by increasing the heat power transmitted from the arc – can make the arc unsteady close to the current zero, resulting in current chopping. Therefore it is important to discuss the stability of the arc. Mayr was the first, who investigated the stability of the arcs burning in gases. He examined the behavior of the arc in the circuit of Fig. 2.17, which represents a CB terminal fault in a simple power network. By solving the differential equation of this circuit, Mayr demonstrated that the stability criteria of an arc burning in a gas is

$$C \cdot R_{\text{arc}} < \tau_{\text{arc}}$$

(2-12)

where $R_{\text{arc}}$ is the arc resistance, $\tau_{\text{arc}}$ is the arc time constant and $C$ is the capacity in the circuit of Fig. 2.17. The arc remains stable if the speed of the energy flow from the capacitor to the arc and vice versa is relatively high that is, it can follow the changes of the arc characterized by its time constant.

b) The stability of an arc in vacuum is different from the stability of an arc in a gas. In vacuum, the arc burns in the metal vapor issued from the electrodes. The most obvious difference between the two arc types is that with small currents – up to about 100…150 A – there is only one arc spot in vacuum, and it forms only on the surface of the cathode. Consequently, there is no anode drop. Within the thin metal vapor plasma, the pressure is about 105 Pa (1 bar), and it is surrounded by vacuum. The electrodynamic compressing forces balance out the pressure of the metal vapor (Fig. 2.18). When approaching the current zero of an AC current, the cooling effect of the cathode becomes stronger. This reduces the inner vapor pressure and the magnetic pressure further squeezes the thin current filament, finally quenching the arc. This is the pinch effect, which results in an unstable arc, and leads to the interruption of the current before its natural zero, namely to current chopping.
3. Switch-off processes

We have seen that successful breaking of electrical circuits needs the eventual blocking of arc re-ignition. Successful interruption results in the initial state (5) of the switching device in Fig. 2.1. Thermal or dielectric re-strike can be caused by the transient recovery voltage (TRV) appearing across the switching contacts after a current zero. The essential goal of dealing with switching transients is to determine the time-function of the TRV, which is responsible for arc re-ignition. Only after the arc has disappeared in a current zero is it possible to prevent re-strike. We can say that the arc “synchronizes” the moment of interruption and the initiation of the TRV to the current zeros. The switch-off processes are actually current breakings, during which the effect of the arc are to be considered as well.

Understanding of these phenomena is easier, if we begin with models, in which the influence of the arc is neglected. To be more precise, we exploit the fact that the arc synchronizes the current interruption with the current zeros, but we disregard any other effects of the arc. Namely, we assume an ideal switch that opens exactly at the time instant of a current zero. In this ideal case, the current to be interrupted and the voltage across the terminals of the switching device after switch-off are independent of the arc. These are the independent current and the independent recovery voltage. When breaking fault currents in HV circuits, the arc voltage is negligible to the supply voltage, therefore this simple model provides a reasonable picture of reality. The time-function of the TRV would be different, if a current flowing through an arc was interrupted. Here we deal only with the interruption of terminal faults.

Considering operating currents, we discuss the interruption of low inductive currents, where we take into account the effects of the arc as well. Finally we will treat fault current interruptions in LV AC circuits, where the arc plays a crucial role in influencing the current and voltage time-functions.

3.1. Ideal interruption of an HV terminal fault

The circuit of Fig. 2.19 models a terminal fault, namely a short-circuit occurred at the terminals of a CB. There is no other component in the circuit between the switch and the fault. This and the circuit used for modeling switch-on (Fig. 2.2) are dissimilar in two points. First, the current model includes the resultant parallel capacitance \( C \) of the network, which plays a major role in determining the TRV. During calculation of the fault current, this \( C \) could be neglected, because \( 1/\omega C > \omega L \) – the current through it has been very small. The other difference is that there is a resistance \( r \) parallel to the contacts of the CB in the model of Fig. 2.19. This \( r \) takes into account the resistance of the post-arc.

As a first approximation, we neglect the serial and parallel resistances in the model of Fig. 2.19, that is \( R=0 \), and \( r=\infty \). This damping - free model is shown in Fig. 2.20a. It is worthy of notice, that the condition of \( R=0 \) is close to the reality of fault interruption in HV circuits, as \( \cos \phi =0.1 \) there.
The moment of contact opening (\(t=0\)) coincides with the natural current zero of the steady-state prospective short-circuit current \(i\). We assume that all switch-on transients has diminished by this time. We seek the voltage across the switch terminals after the time instant of switch-off. This voltage equals to the capacitor voltage \(v_c(t)\). Provided that \(\frac{1}{\omega C} > \frac{1}{\omega L}\), after a long time, \(v_c\) becomes identical to the supply voltage that is, \(v_{cs}(t)=v(t)=V_m \cos \omega t\). This voltage, the steady-state recovery voltage together with the prospective short-circuit current \(i\) lasted until its zero (\(t=0\)) is plotted in Fig. 2.20.b. Since the circuit is solely inductive, this current lags behind the voltage by an angle of \(\pi/2\). The picture clearly indicates that at \(t=0\), \(v_{cs}(0)=V_m\). The capacitor voltage is the sum of two components in this case too:

\[
v_C(t) = v_{Cst}(t) + v_{Ctr}(t).
\]

(2.13)

We still do not know the transient time-function \(v_{cs}(t)\), but we know that the capacitor voltage has been zero prior to switch-off, since the closed switch shunted out \(C\). This voltage cannot jump, therefore its initial value is zero after current interruption, \(v_c(0)=0\). From these assumptions, the equation

\[
v_C(0) = 0 = V_m + v_{Cst}(0)
\]

(2.14)

follows, which results in \(v_{cs}(0)=V_m\). This is the initial value of the transient component, which is followed by a periodic oscillation caused by the current \(i\) in the \(L-C\) circuit of the network. There is no damping in the oscillation (\(R=0\)), and its natural frequency

\[
\omega_0 = \frac{1}{\sqrt{LC}},
\]

(2.15)

which is significantly higher (of the order of krad/s) than the angular frequency \(\omega\) of the power supply. The time-function of the transient component (in other words oscillating component):

\[
v_{Ctr}(t) = -V_m \cos \omega_0 t,
\]

(2.16)
which starts with zero steepness. It is easy to verify that \( i_{\text{sc}}(0)=0 \), as no current has been flowing in the \( L-C \) circuit before switch-off, and the current has been interrupted exactly in its natural zero. From this assumption:

\[
C \cdot \left. \frac{dv}{dt} \right|_{t=0} = i_{\text{sc}}(0) = 0
\]

(2-17)

consequently, just like \( v_{\text{ct}} \), the initial slope of the resultant \( v_c \) is zero (see Fig. 2.20c). It follows from this that the initial steepness of \( v_{\text{ct}} \) is also zero.

Fig. 2.20.d shows the time-functions \( v_{\text{ct}}(t) \) and \( v_c(t) \), the latter one as the sum of \( v_{\text{cs}}(t) \) and \( v_{\text{cd}}(t) \). The time-function \( v_c(t) \) is the voltage appearing across the terminals of the switching device after the current interrupted, and it is called transient recovery voltage (TRV). In this case, the oscillation of the TRV has only one frequency: \( f_0 = \omega_0 / 2\pi \).

The time-function of the TRV:

\[
v_c(t) = V_m \left( \cos \omega t - \cos \omega_0 t \right)
\]

(2-18)

and its peak factor:

\[
k_p = \frac{v_c(t)}{V_m}
\]

(2-19)

The peak factor is only slightly smaller than \( k_p=2 \) – we can say that the difference is negligible – since the steady-state recovery voltage \( v_{\text{cs}}(t)=V_m \cos \omega t \) remains practically constant \( (V_m) \) during a half cycle of the oscillating transient.

If we take into account the serial resistance \( R \) neglected previously, the phase shift between the fault current and the supply voltage will be less than \( \pi / 2 \), although in HV circuits the difference from \( \pi / 2 \) is usually negligible. Not negligible however, is the damping of the oscillating part by a serial damping factor of

\[
\delta_s = \frac{R}{2L}.
\]

(2-20)

Besides, the natural frequency also changes, it will be slightly less than in the un-damped case:

\[
\omega_1 = \sqrt{\omega_0^2 - \delta_s^2}.
\]

(2-21)

Because of the lagging short-circuit current, of the reduced oscillation frequency, and above all, because of the damping, the peak factor of the TRV will be definitely less than 2.

Fig. 2.21. Ideal interruption of fault in a HV circuit with serial damping

Based on the previous assumptions, we can use a simplified, approximate formula to calculate the damped TRV after a fault interruption in an HV circuit:

\[
v_c(t) = V_{\text{ra}} \left( 1 - e^{\delta_s t} \cdot \cos \omega_0 t \right)
\]
which is shown in Fig. 2.21. It is clear that, just like in the un-damped case, the initial slope of the TRV is zero. We can say that the error we make by using this equation is in favor of safety.

If we take into account the resistance \( r \) parallel to the switch \((R \neq 0; \; r \neq \infty)\), only the oscillating component of the TRV changes. On the one hand, its damping becomes stronger, since the resultant damping factor \( \delta \) is the sum of a serial \( \delta_s \) and a parallel \( \delta_p \) part:

\[
\delta = \frac{1}{2} \left( \frac{R}{L} + \frac{1}{rC} \right) = \frac{R}{L} + \frac{1}{2rC} = \delta_s + \delta_p.
\]  

(2-23)

On the other hand, if the transient voltage is periodic, the difference between the damped and un-damped natural frequencies will not be negligible:

\[
\omega_0 = \sqrt{\omega_0^2 - (\delta_p - \delta_s)^2}.
\]  

(2-24)

It is clear from this relation that the damped and un-damped oscillation frequencies can theoretically be equal, if \( \delta p = \delta s \). In practice however, \( \omega s < \omega 0 \), since \( \delta p \gg \delta s \).

Again in favor of safety, we can use a simplified, approximate equation to calculate the TRV after a fault in a HV circuit with serial and parallel damping:

\[
v_i(t) = V_m \left( 1 - e^{-\delta t} \cdot \cos \omega_0 t \right),
\]  

(2-25)

the plot of which is very similar to that of the serially damped case in Fig. 2.21.

### 3.2. Interruption of small inductive currents in HV circuits

Not only the high fault currents can cause problems during switch-off. Sometimes, the interruption of much smaller load currents can also be difficult, if the arc re-ignites after extinction. Two such cases exist. One of them is the breaking of capacitive load currents, like the switch-off of an idle overhead line or cable or a capacitor bank. Here we deal only with the other case, namely with the interruption of small inductive currents. In practice, this can happen when switching off the no-load current of large transformers or medium voltage asynchronous motors, and it is dangerous only if the CB chops the arc current. Therefore we have to consider the arc voltage during the discussion of this phenomenon.

![Fig. 2.22. Interruption of small inductive current; equivalent circuit](image)

In Fig. 2.22, \( L_2 \) represents the inductance of an idle transformer, and \( C_2 \) its stray and interturn capacitances. The small inductance \( L_1 \) has a role only at re-ignition. The CB interrupts the current \( i \) at \( t=0 \) with chopping. The time-functions are plotted in Fig. 2.24, with the assumption that prior to interruption:

\[
v_{arc} = v_1 \cdot v_2
\]  

(2-26)

and

\[
v_1 = V_{arc} \cdot \frac{di}{dt},
\]
and the difference of the two capacitor voltages provide the TRV after interruption.

Fig. 2.23. Interruption of small inductive current; time-functions

It can be observed in Fig. 2.23. that the voltage \( v_1 \) on the supply side tends to the supply voltage \( V_m \) – considered as constant – with a damped oscillation of the frequency

\[
\omega_1 = \frac{1}{\sqrt{L C_1}}.
\]

(2-28)

The voltage \( v_1 \) continuously passes the moment of current break with the same steepness. The slope of the voltage \( v_2 \) is also continuous at this time instant, although \( v_2 \) oscillates around zero with the frequency of

\[
\omega_2 = \frac{1}{\sqrt{L C_2}}.
\]

(2-29)

and tends to zero with damping \( (\omega_2 < \omega_1) \). The TRV starts from a finite value with a high steepness equal to that of the arc voltage; therefore it can easily re-ignite the arc. Assuming dielectric re-ignition, re-strike occurs at \( V_0 \), as it can be seen in Fig. 2.23. A high-frequency discharge current \( i_3 \) starts to flow through the arc at this moment in the circuit of \( C_1 - L_3 - C_2 \) (see Fig. 2.22.). The resultant capacitance of two series connected capacitors:

\[
C_r = \frac{C_1 C_2}{C_1 + C_2} < C_1
\]

(2-30)

which is charged to the voltage of \( V_0 \) at the moment of re-strike. Neglecting the losses, the energy stored in the capacitors is converted into the energy of the inductance \( L_3 \):

\[
\frac{1}{2} C_r V_0^2 = \frac{1}{2} L_3 I_{3m}^2
\]

(2-31)

consequently the possible largest peak of the high-frequency discharge current:

\[
I_{3m} = V_0 \sqrt{\frac{L_3}{C_r}}
\]

(2-32)

and its angular frequency:
\[ \omega_3 = \frac{1}{\sqrt{L C}}. \]

(2-33)

The arc carries the 50 Hz current from the supply as well. Figure 2.24 illustrates the current and voltage time-functions after a repeated chopping and re-ignition, and the final arc extinction on a smaller time-scale than in the previous figure. It is observable that the risk of re-ignition decreases toward the natural zero of the power-frequency current, as both the chopped current and the stored magnetic energy becomes smaller and smaller. However, if re-strikes continue after the 50 Hz current zero, the chance of successful arc quenching will be less, the voltage gets higher, finally leading to sparkovers and probably to a short-circuit.

Fig. 2.24. Repeated re-ignition of arc current; time-functions

3.3. Interrupting a LV terminal fault

We have already mentioned in section 2.2.2.2 that the voltage of the short, non-linear switch arc is comparable to the supply voltage; it often surpasses the supply in LV systems. In an AC circuit this leads to the distortion of the prospective current, it will differ from sinusoidal. We will determine the time-function of the arc current \( i(t) \) from the approximate formula (2-9) of the arc voltage \( v_{arc}(t) \) for an LV circuit modeling a terminal fault. The circuit is shown in Fig. 2.25. We will discuss the interruption with and without current limitation. Applying the principle of superposition will yield the current time-function \( i \) in both cases. At the moment of contact opening \((t=0)\), a transient current \( i_2(t) \) begins to flow – due to the initiated arc voltage –opposite to the current \( i_1(t) \). The sum of these two currents results in the time-function we seek:

\[ i(t) = i_1(t) + i_2(t). \]

(2-34)

3.3.1. Interruption without current limitation

It can be observed in Fig. 2.26 that after fault occurrence, a prospective current \( i_r \) flows until the moment of contact separation. We assume that this current is sinusoidal, although it can contain a DC component as well. Contact separation happens only after the first current zero, therefore the peak of \( i_r \) can evolve. The increase of the gap between the contact members raises the arc voltage, thus results in a more and more distorted and decreasing current \( i \), compared to \( i_r \) that would flow if the contacts remained closed. Probably more important is the shift of the current zeros. The zeros of \( i \) repeat each other more rapidly than that of \( i_r \). As a consequence, the steady-state recovery voltage will be smaller at these time instants, resulting in smaller initial value of the oscillating voltage and eventually in smaller TRV.
The voltage of the capacitor \( C \) cannot jump. As in reality, it has to decrease with a finite steepness. No matter if the TRV is periodic or aperiodic, after current zero, it must continue with the same slope. Therefore, to plot the TRV, we have to modify the arc voltage – originally described by (2-9) – in the short time interval close to the moment of interruption, as shown by the dashed line in Fig. 2.26. This modification has only a minor influence on the current, which cannot be observed in the figure.

Fig. 2.26. Interruption of a terminal fault without current limitation in an LV circuit; time- functions

If we take the current zero when the current passes from negative to positive as the moment of contact separation, then the time-function of the arc current up to its first zero:

\[
i(t) = \frac{V_n}{Z} \cdot \sin \omega \cdot (t + t_s) - \frac{V_{ak}}{R} \left(1 - e^{-\frac{t}{\tau}}\right) - \frac{I_0}{R} \left[t - T \cdot \left(1 - e^{-\frac{t}{\tau}}\right)\right],
\]

(2-35)

where \( t_s \) is the time instant of contact separation. This equation was obtained with the method of superposition.

Figure 2.26 illustrated a successful interruption, when the arc did not re-ignite after the second current zero, and the current remained steadily zero. We have seen in section 2.2.2.3 that, because of the strong de-ionizing and cooling effect of the relatively high mass electrodes, the primary cause of re-strike at low voltages is the spark breakdown. To examine re-ignition processes, we have to know the time-function of the ignition voltage \( v_{ign} \) appearing across the contact members (Fig. 2.15). Formula (2-10) provides a simple approximation of \( v_{ign} \). Figure 2.27 shows the example of an unsuccessful interruption, when the periodic TRV exceeded the re-ignition voltage, causing a re-strike.

Fig. 2.27. Unsuccessful interruption of a LV terminal fault, no current limitation

### 3.3.2. Interruption with current limitation

In case of current limiting circuit breakers, the peak \( I_{Fm} \) of the prospective current \( i_x \) cannot develop. The contacts open at a small momentary value of \( i_x \), and the arc voltage rises so fast that it soon exceeds the supply voltage. This effect is usually provoked by deion plates, discussed in chapter 6. It can be seen in Fig. 2.28 that the let-through current \( I_{lt} \), namely the limited peak, is less than \( I_{Fm} \), a merely 60 % of that. With real circuit breakers, we can expect even a much stronger effect; therefore it would not be illustrative to plot a real process.
here. A necessary condition of current limitation is the fast contact separation. After the contacts are apart, a rapid and permanent increase of the arc voltage above the supply voltage makes the interruption of the current with less than the prospective peak possible.

Formula (2-35) obtained by means of superposition is still valid for the current time-function, if we count the moment of contact separation $t_\text{s}$ from the time instant when $i_F$ passes zero to the positive direction. The differential equation

$$v_{\text{arc}} = v - i \cdot R - L \cdot \frac{di}{dt}$$

(2-36)

valid for the circuit of Fig. 2.25 yields the time function of the prospective current. The relation between the let-through current $I_\text{lt}$ and its time instant $t_{\text{m}}$ is easily derivable, as $di/dt=0$ at the moment of a $t_{\text{m}}$.

$$I_\text{lt} \cdot R = v(t_{\text{m}}) - v_{\text{arc}}(t_{\text{m}}).$$

(2-37)

![Diagram](image-url)

Fig. 2.28. Interruption of a LV terminal fault with current limitation; time-functions
3. fejezet - Thermal transients

It is important to be familiar with the principles and basic calculation models of thermal processes taking place in equipment – like energy converters, conductors, switchgears and switching devices, etc. – of electric power systems. On the one hand, the ability to calculate temperature rise makes possible the economic design of the electrical apparatus without over-sizing. Inappropriate design can cause harmful overheating leading to operating failures. On the other hand, the operation of some of the electrical switching devices – like fuses, bimetallic releases, thermal relays, etc. – is based on heating, and the operation of others – like circuit breakers, switches – is affected by the thermal effects of the electric arc.

The current flowing in the electrical conductors generates heat, namely thermal energy. One portion of this Joule-heat raises the temperature of the conductor, whereas another portion is transmitted to the environment. During this transient thermal process, the conductor temperature \( \vartheta \) (K) increases until it reaches steady-state, in other words heat balance. From this moment on, all the generated Joule-heat passes to the environment. Heat can be transferred on three different ways: heat conduction, thermal radiation and convection.

All the three heat transfer modes are taken into account in the heat transfer coefficient – or film coefficient – \( \alpha \) (W/m\(^2\)K) in the following equation:

\[
P = \alpha \cdot S \cdot \tau,
\]

(3-1)

where \( P \) (W) is the thermal power generated in the conductor, \( S \) (m\(^2\)) is the heat transfer surface area, and \( \tau \) is the difference in temperature between the surface \( \vartheta \) (K) and the surrounding environment \( \vartheta_{amb} \) (K):

\[
\tau = \vartheta - \vartheta_{amb}.
\]

(3-2)

Table 3.1 compares the properties and possible mathematical simplifications of slow and fast thermal processes. Operating and overload currents can cause slow, whereas short-circuits usually result in fast temperature rise.

Table 3.1.

<table>
<thead>
<tr>
<th>Slow temperature rise</th>
<th>Fast temperature rise</th>
</tr>
</thead>
<tbody>
<tr>
<td>caused by operating and overload currents</td>
<td>caused by short-circuits</td>
</tr>
<tr>
<td>Most of the heat is transferred to the environment This condition is satisfied, if the duration of heating ( t_s ) is of the same order of magnitude as the thermal time constant ( T_s ).</td>
<td>The portion of heat transmitted to the environment is negligible. This condition is satisfied, if the duration of the fault ( t_{sc} ) is much smaller than the thermal time constant ( T_s ).</td>
</tr>
<tr>
<td>The time of heating ( t_s ) is much higher than the electrical time constant ( T ) of the circuits (( t_s &gt; T )); switch-on transients are negligible.</td>
<td>Switch-on transients can be negligible only if ( t_{sc} &lt; T_s ).</td>
</tr>
<tr>
<td>Temperature rise can be calculated with the rms value of the AC current.</td>
<td>Rms current value can be used for the calculations, only if switch-on transients are negligible that is ( t_{sc} &gt; T ).</td>
</tr>
<tr>
<td>If only minor temperature rise occurs, then the temperature dependence of the electrical resistivity ( \rho ), the specific heat ( c ), and the film coefficient ( \alpha ) are negligible that is, constant values can be used.</td>
<td>If the temperature rise is significant, then the temperature dependence of the electrical resistivity ( \rho ), the specific heat ( c ), and the film coefficient ( \alpha ) have to be taken into account.</td>
</tr>
</tbody>
</table>
Fig. 3.1. Model for temperature rise calculation

Figure 3.1 shows an infinite long, blank conductor carrying a current $i$, and having a direct contact to the environment on its surface. We will use this simple model to explain the basics of slow and fast transient thermal processes. The mathematical representation includes only a $dx$ long section of the conductor with a volume of $V=A \cdot dx$ and with a contact surface of $S=K \cdot dx$, where $A$ ($m^2$) is the cross-section of the conductor and $K$ ($m$) is its circumference. We assume uniform temperature distribution throughout this volume, and uniform current-density distribution in the cross-section.

Fig. 3.2. Current-density distribution in a standalone, flat busbar

However, we have to be aware of the limits of such a simple model. Assuming uniform current-density distribution might result in a significant error with AC currents, as the electromagnetic skin and proximity effects make this distribution non-uniform. This phenomenon has essential influence with fast thermal transients, as the Joule-heat distribution reflects the distribution of the current, and there is no enough time for the temperature to balance out across the cross-section. As a consequence, the temperature dependent material properties will vary from point to point, affecting the initial current distribution. Figure 3.2 illustrates the current-density distribution along the horizontal symmetry plane of an infinite long, flat, copper busbar with a cross section of 100x10 mm$^2$. We assume that the current return path is infinitely far away, that its proximity does not affect the distribution in the standalone busbar. During the calculation, the resistivity was taken constant and the frequency was 50 Hz. The rate of the maximum and minimum rms current-densities is $J_{\text{max}}/J_{\text{min}}=2.14$. Compared to the DC current-density distribution, the difference is also significant. This significant non-uniformity comes from the fact, that the size $b=100$ mm is much greater than the skin depth in copper at 50 Hz, $\delta_{50Hz} \approx 10$ mm. Although when calculating slow thermal processes the temperature distribution can be assumed uniform, the uneven current-density must still be considered, as it results in increased Joule-heat. In the example of Fig. 3.2, the loss is increased by 14 % compared to the DC loss.

Taking the heat transfer coefficient $\alpha$ as constant can further increase the calculation error. The steady-state temperature distribution of the three-phase metal enclosed busbars of an HV switchgear and the flow of the inner SF$_6$ gas and the outer air can followed in Fig. 3.3 for two different configurations. The non-uniform current-density distribution, the temperature dependent material properties, the convective heat transfer between the metal surfaces and the gas, and the radiation of the solid surfaces have all been taken into consideration by means of coupled field finite element simulations. The temperature difference between the busbars carrying the same amount but symmetrically shifted rated currents is obvious. Furthermore, the non-uniform temperature distribution in the enclosure is clearly seen. Besides the gas flow, the uneven current-density distribution in the enclosure is also responsible for this effect.
In the following sections we discuss the basic, analytical calculation methods of slow and fast temperature rise. The discussion is based on the simple model of Fig. 3.1. Finally we deal with the allowed temperature rise in electrical equipment.

1. Slow temperature rise

In this case, the temperature rise of the conductor in Fig. 3.1 can be calculated with the rms current \( I \). The resistivity of the conductor material is \( \rho \ (\Omega m) \), and the conductor resistance is \( R \ (\Omega) \).

A current previously flowing in the conductor – and a possible cooling after current break – can cause an initial temperature deviation \( \tau_o = \tau(0) \) from the ambient temperature \( \vartheta_{\text{amb}} \), namely the initial temperature of the conductor at the moment of current make \((t=0) \) is \( \vartheta = \vartheta_{\text{amb}} + \tau_o \). In this case, the time function of heating takes the following form:

\[
\tau(t) = \tau_{st} \cdot \left(1 - e^{-\frac{t}{T_h}} \right) + \tau_o \cdot e^{-\frac{t}{T_h}}.
\]

(3-3)

where \( T_h \ (s) \) is the thermal time constant:

\[
T_h = \frac{cJ}{\alpha S} = \frac{cA}{\alpha K}.
\]

(3-4)

The steady-state temperature rise \( \tau_{st} \):

\[
\tau_{st} = \frac{\varrho}{\alpha S} = \frac{J^2 R}{\alpha K} = \frac{J^2 \rho A}{\alpha K},
\]

(3-5)

where \( J \ (A/m^2) \) is the current-density:

\[
J = \frac{i}{R}.
\]

(3-6)

The second term in formula (3-3) represents the cooling process of a conductor carrying no current and having an initial temperature rise \( \tau_o \). This term can be omitted, if the current starts when the conductor has already cooled back to the ambient temperature that is, if \( \tau_o = 0 \). Fig. 3.4. shows time functions of heating and cooling processes.
Short time heating is a typical example of slow thermal processes. In this case, the temperature rise of the conductor $\tau_{\text{per}}$ is less than the steady-state value $\tau_{\text{st}}$, since the current $I$ flows only for a short time until the conductor temperature reaches a permitted value. After this short duration $(t < 2.5 \cdot T_h)$, the conductor cools back to the ambient temperature $\vartheta_{\text{amb}}$ during $t < \frac{3}{4} \cdot T_m$. Figure 3.5 shows a similar heating and cooling process. Applying the general relation (3-16):

$$\tau_{\text{per}} = \tau_{\text{st}} \cdot \left(1 - e^{\frac{-t}{\tau_h}}\right) + \tau_0 \cdot e^{\frac{-t}{\tau_h}}.$$  (3-7)

If the temperature rise is generated by a current, then its value is proportional to the current square. For instance, the permitted heating $\tau_{\text{per}}$ is proportional to the square of a limiting current $I_l$ at which the circuit must be disconnected from the supply. Therefore, equation (3-7) can be written with currents:

$$I_1^2 = I_2^2 \cdot \left(1 - e^{\frac{-t}{\tau_h}}\right) + I_0^2 \cdot e^{\frac{-t}{\tau_h}}.$$  (3-8)

If we know the thermal time constant and the current values, we can determine the duration of the heating. For instance, the operating time of a bimetallic release or the melting time of a fuse:

$$\tau_{\text{f}} = \frac{T_h}{\ln \frac{I_2^2}{I_1^2}}.$$  (3-9)

### 2. Fast (short-circuit) temperature rise

The current $i$ started at $t=0$ heats up the conductor of Fig. 3.1 from an initial temperature $\vartheta_i$. Under the duration of the short-circuit – up to the moment of $t=t_{\text{sc}}$ – the conductor temperature rises to $\vartheta_{\text{sc}}$. Depending on the conductor size, the temperature rise is usually higher than with slow processes. Therefore we have to take into account the temperature-dependence of the specific heat and the electrical resistivity. This temperature dependence can be approximated by the following formula:

$$\frac{\vartheta}{\vartheta_i} = \frac{\vartheta_{\text{sc}}}{\vartheta_0} \cdot \left[1 + \alpha_{\vartheta} \left(\vartheta - \vartheta_0\right)\right],$$  (3-10)
where $\alpha$ (1/K) is the temperature coefficient of the conductor material. The resistivity $\rho$ and the specific heat $c$ are related to the temperature $\vartheta$, whereas $\rho_o$, $c_o$ and $\alpha_o$ correspond to $\vartheta_o$. We note, that the temperature dependence of the specific heat $c$ is negligible up to 300 °C, therefore up to this temperature, instead of $\alpha$, the heat coefficient of the resistivity can be used. We have seen that the heat transferred to the environment is negligible, since the duration of the fault is much shorter than the thermal time constant ($t \gg T_m$). During the calculation we have to consider the momentary value $(i)$ of the current that is, usually we cannot neglect the switch-on transients. As we disregard the heat transmission to the environment, we relate the temperature rise $\tau$ to $\vartheta_o$, corresponding to $\rho_o$, $c_o$ and $\alpha_o$, instead of the ambient temperature. In this case

$$\tau = \vartheta - \vartheta_0$$

(3-11)

During the time $t_{sc}$, the initial temperature $\vartheta_i$ of the conductor grows to $\vartheta_{sc}$. This can be obtained from the following formula:

$$J_{th}(t_{sc}) = \frac{c_o}{\vartheta_0} \ln \frac{\vartheta_{sc} - \vartheta_0}{\vartheta - \vartheta_0}$$

(3-12)

where

$$J_{th}(t_{sc}) = \int_{0}^{t_{sc}} i^2 dt = A^2 \int_{0}^{t_{sc}} t^2 dt$$

(3-13)

is the Joule-integral. The manufacturers provide the thermal limit current $I_{th}$ belonging to the permitted temperature rise of the equipment together with the thermal time limit $t_{sc}$. The Joule-integral with these parameters:

$$J_{th} = I_{th}^2 \cdot t_{sc}$$

(3-14)

For instance, if the thermal limit current $I_{th1}$ and the corresponding time $t_{sc1}$ are given, the value of $t_{sc2}$ belonging to $I_{th2}$ can be easily expressed from the relation

$$I_{th1}^2 \cdot t_{sc1} = I_{th2}^2 \cdot t_{sc2}$$

(3-15)

3. Permitted temperature rise

If the temperature of electrical equipment and switching devices or the temperature of their components is less than a permitted value $\vartheta_{per}$, or their temperature rise $\tau_{per}$ does not exceed an allowed maximum, then their operation is safe.

In case of metals, the decrease of the tensile strength limits the possible temperature rise. Generally, a reduction to 85% of the cold value can be tolerated. Figure 3.6 illustrates the temperature variation of the permitted tensile strength $\sigma_{per}$ for copper in relative values. It can be observed that the degree of reduction is much more with permanent (curve 2) than with short time heating (curve 1). This indicates higher permitted tensile strength if the duration of the heating is short. The variation of the relative tensile strength in case of permanent heating is plotted in Fig. 3.7 for another two materials: hard-drawn aluminum (curve 1) and bronze (curve 2).
In case of insulating materials, not only the mechanical, but also the electrical properties change with temperature. For instance, the dielectric strength, the insulation resistance, or the loss tangent ($\tan \delta$) are temperature dependent, as it can be followed for dielectric strength in Fig. 3.8. Regarding permissible temperatures, insulators are grouped into classes (e.g. class A: $\vartheta_{pr}=105 \, ^\circ\text{C}$).

Fig. 3.7. Relative tensile strength of hard-drawn aluminum and bronze as function of temperature

Fig. 3.8. Dielectric strength of insulators as function of temperature; 1. paper, 2. porcelain, 3. glass
4. fejezet - Mechanical transients

The dynamic forces caused by the varying currents during switch-on processes – especially at the peak of short-circuits – play a major role in the operation of electric power equipment, particularly in switchgears and in their components, the electrical switching devices. On the one hand, these dynamic forces are exploited in state-of-the-art devices, for instance to help extinguish the arc. On the other hand, neglecting of these forces during the design of the equipment can lead to failures, like deformation or welding. It is unfortunate that mechanical stress produced by these forces goes hand in hand with increased thermal stress. High deforming forces take place exactly when the increased temperature reduces the mechanical strength of the conductors.

The maximum permitted electrodynamic force corresponds to the peak withstand current \( I_p \). This is the value of a momentary current that a circuit or a switching device in the closed position can withstand without damage.

Similar to the thermal processes, we are concerned with analytical methods of calculation. We neglect the proximity of ferromagnetic and conducting materials, and we do not take into account the non-uniform current-density distribution with AC currents. We will use two different approaches. In one of them, we assume zero cross sectional area that is, we model the conductors as thin current filaments. In the other approach, we keep the cross sectional area, but we assume a uniformly distributed current in the conductor. Nevertheless, we have to keep in mind that, if the cross sectional size of the conductor is larger than the skin depth at the frequency of investigation, and if the distance between the conductors is of the same order of magnitude as the cross sectional size, then these simplifications lead to inaccurate results. For instance, the calculated force between the two copper busbars of Fig. 4.1 is fairly different with uniformly distributed – DC and 50 Hz AC currents. We can infer from the difference in current-density distributions with the same and opposite current flow, that in case of AC, the magnitude of the force depends also on the direction of the current. Higher the width \( b \) compared to the skin depth \( (\delta \approx 10 \text{ mm}) \) and smaller the distance between the busbars, more pronounced is the deviation from the DC distribution. If the two busbars carry a current in the same direction (Fig. 4.1.b), the current is constrained away the adjacent busbar, resulting in smaller force than with DC, or than with opposite direction. In the latter, opposite case (Fig. 4.1.a), the current is constrained toward the gap between the conductors, resulting in less force than with DC. The ratios representing the magnitude of non-uniformity: \( J_{\text{max}}/J_{\text{min}} = 3.37 \) and 2.87. Consequently, the losses are higher than with a standalone busbar. We note that metals in the proximity change the current-density distribution, as current can be induced in them. Ferromagnetic materials can affect the distribution, even without induced current (e.g. laminated iron).

![Fig. 4.1. Current-density distribution in parallel, flat busbars; a) opposite, b) same direction of current flow](image)

The analytical calculation models we discuss in this chapter help us to understand the physical phenomena. The results of these methods can be used to verify the more precise, numerical solutions, for instance the outcome of finite element simulations. The chance of mistakes is far more when creating complex numerical simulation models, therefore the knowledge of simple calculation methods is a prerequisite for the use of these techniques, even if we use commercial simulation software. We explain two analytical methods. One of them is based on Biot-Sawart law, the other one can be deduced from the variation of magnetic energy. After the basic methods, we investigate the direction of forces, the forces evoking in current constrictions, and finally the effect of electrical transients.
1. Force calculation based on Biot-Sawart law

This method is appropriate, when the finite long conductors can be substituted with current filaments, namely their cross-section, or the influence of the cross section on the results is negligible. This is the case, when the distance between the conductors is much more than their cross-sectional size.

![Parallel, filamentary conductors](image)

In the following section, we determine the forces acting on the finite long, straight conductor segments of closed circuits, and the forces between infinite long, parallel busbars with square cross-sections. Let the parallel filamentary conductors 1 and 2 be at the same plane at a distance of R, and the momentary values of the currents flowing in them \( i_1 \) and \( i_2 \) (Fig. 4.2). Form the Biot-sawart law it can be deduced that the force acting perpendicular on the \( \ell_1 \) long section of conductor 1:

\[
F_{12} = i_1 \cdot i_2 \cdot k_{12} \cdot 10^7 (N),
\]

(4-3)

where the dimensionless form factor \( k_{12} \) depends only on the conductor arrangement:

\[
k_{12} = \frac{D \sum S \cdot \sum \sigma}{R} = \frac{\sum D \cdot \sum S \cdot \sum \sigma}{R}.
\]

(4-4)

According to Fig. 4.3, \( D \) denotes the diagonal of the trapezoid, and \( S \) denotes its sides. Index 1 indicates the force acting on conductor 1, and index 2 shows that this force is generated by the current flowing in conductor 2.

With parallel conductors, the forces acting on the two segments are opposite, but they have the same magnitude. Thus \( F_{12} = F_{21} \) and \( k_{12} = k_{21} \).

In the special case, when conductor 2 can be taken as infinite, then the force acting on conductor 1:

\[
F_{12} = \frac{2 \sigma_2}{R} \cdot \ell_1 \cdot 10^7 (N).
\]

(4-5)
Another practical example is the force between infinite long, parallel busbars or grouped busbars with square cross sections. By assuming uniform current-density distribution, and by dividing the conductor cross sections into elementary current filaments, the resultant form factor $k$ can be obtained from the addition of the form factors between the elementary filaments. This resultant $k$ is plotted in Fig. 4.3 as function of two dimensionless geometric parameters $r-a/(a+b)$ and $a/b$. The force between the $l$ long busbars at a mean distance $r$:

$$F = i_1 \cdot i_2 \cdot \frac{2 \pi}{r} \cdot k \cdot 10^7.$$  

(4-6)

If $k=1$, this formula provides the force between two parallel, filamentary conductors at a distance of $r$. It might be interesting that $k \geq 1$, if the smaller side $b$ of the busbars face each other.

### 2. Force calculation based on the change of magnetic energy

If there is no ferromagnetic material in the vicinity of the electrical circuit, then the force acting in direction $s$ can be derived from the change of magnetic energy:

$$F_s = -\frac{1}{2} \cdot i^2 \cdot \frac{dL(s)}{ds},$$  

(4-7)

where $L(s)$ is the self-inductance of the circuit, and $L(s)$ varies with the parameter $s$. 
Mechanical transients

Fig. 4.4. Force acting on the unit length of a circular conductor

We demonstrate the application of this method within a single electrical circuit with the practical example of a single conductor turn. We determine the force per unit length $f_r$ acting on a circular conductor having a circular cross section in Fig. 4.4. If $R_{\cap} > r$, the self-inductance of one turn:

$$L = \mu_0 \cdot R \left( \ln \frac{3R}{r} - 1.75 \right),$$  
(4-9)

from which the radial force acting (in direction R) on the total length of the conductor:

$$F_R = -\frac{1}{2} \cdot \frac{d}{dr} \left( \frac{dM(R)}{dr} \right) = 2 \cdot \pi \cdot i^2 \cdot 10^7 \cdot \left( \ln \frac{3R}{r} \cdot 0.75 \right) (N),$$  
(4-9)

and the force acting on a unit length of the turn:

$$f_r = \frac{F_r}{2\pi R} = \frac{2\pi \alpha \cdot 10^7}{R} \cdot \left( \ln \frac{3R}{r} \cdot 0.75 \right) (N/m).$$  
(4-10)

Fig. 4.5. Force between circuits

Force acts not only within one circuit, but between separate circuits as well. The two circuits in Fig. 4.5 are magnetically coupled. The total magnetic energy if there is no non-linearity:

$$W_L = \frac{1}{2} \cdot \frac{d}{ds} \left( M \right) = \frac{1}{2} \cdot \frac{d}{ds} \left( \frac{1}{2} \cdot \frac{d}{ds} \left( M \right) \right),$$  
(4-11)

where $M$ is the mutual inductance between the circuits. By assuming a displacement $ds$ between the circuits, only the value of $M=\text{M}(s)$ changes. Therefore

$$F_x = -i_1 \cdot i_2 \cdot \frac{dM(s)}{ds}.$$  
(4-12)

3. Direction of force

---

Created by XMLmind XSL-FO Converter.
Fig. 4.6. a); b);Models to determine the direction of forces

It is worth memorizing the direction of force in some basic conductor arrangements (Fig. 4.6.a) and considering some physical phenomena that help determining the direction (Fig. 4.6.b). The major rules:

1. Parallel conductors attract each other if the currents flow in the same, and repel if the currents flow in opposite direction.

2. Current loops try to expand.

3. Regarding the force between perpendicular conductors, the conductors can be imagined as components of a closed loop.

4. The density of induction lines is smaller in the direction of the force (Fig. 4.6.b).

![Fig. 4.7. Current filaments in a contact constriction](image)

**4. Repulsive force in current constrictions**

Force always evokes where the current is constrained to a narrow path. This phenomenon is especially unfortunate in the constrictions of contacts, since the repulsive force tries to separate the closed contact members. As a result, the contact pressure reduces, the constriction resistance increases, leading to higher temperatures, and possible welding. According to Fig. 4.7, it is clear that those current filaments which have opposite horizontal components in the two contact members get closer to each other than the filaments carrying currents in the same direction. This explains that the resultant force is repulsive, which force can be determined by the following empirical formula:

\[
F = k \cdot r^2 \cdot 10^7 \cdot \ln \frac{D}{\sigma},
\]

(4-13)

where \(k=1.3...1.5\).

**5. Effect of electrical transients**

Concerning that force is proportional to current square, its effects during electrical transients is especially important. Fig. 4.8 shows the time function of the force during switch-on of an AC current with possible highest current peak: \(I_{\text{max}} \approx 1.8 \cdot I_{\text{st max}}\). The possible greatest force in this case:

\[
F_{\text{max}} = 1.8^2 \cdot F_{\text{st max}} = 3.24 \cdot F_{\text{st max}}
\]

(4-14)

It is more than three times of the force occurring at steady-state peak.

If current flows in a three-phase system, besides the transients, the phase shift between the currents must also be taken into account during force calculation.
Fig. 4.8. Time functions of fault current and force in a single phase AC circuit during switch-on
5. fejezet - General rules of switching device selection

Usually, several switching devices are installed together with associated control, measuring, protective and regulating equipment in electrical switchgears. Selection of the switching devices is part of a complex design process. Considering consumer needs, adaptation to existing network topology, design of the connection diagrams are the first steps to be accomplished to obtain enough information for the selection of the switching devices. Based on these data, one can choose appropriate equipment according to its intended function.

Switching devices installed in switchgears may provide two main functions. One of them is to set and maintain normal, operating conditions, like switching on or off loads, isolation of system parts, etc. The other one is the protective function that can be the automatic and selective disconnection of faulty equipment (consumer, system part, etc.) in case of overcurrent, or the protection of equipment in case of overvoltage.

If we know the intended function, we have to check and examine the technical parameters and characteristics of the switching device.

1. Two different types of electrical properties can be distinguished. Passive properties characterize static conditions, and can be interpreted in the same way for any equipment type. These are the rated voltage, insulation level, rated current and fault withstand characteristics, like short-time and peak withstand currents, thermal time limit. The active properties characterize the operation of the devices; they can be different parameters for different device types. For instance, for CB: rated making current, breaking capacity, rated transient recovery voltage, etc; or for fuses: maximum allowed value of switching overvoltage, characteristics of current limitation, etc; for load switches: breaking capacity of load currents, operating cycles regarding electrical durability, etc.

2. Mechanical properties can be the allowed mechanical load of the terminals, operation cycle regarding mechanical durability and the operation cycles available without maintenance.

3. Installation requirements and ambient conditions have to be satisfied as well. Installation requirements can be different for indoor and outdoor equipment, and for switchgear type that can be enclosed or is enclosure free. Ambient conditions are the temperature, elevation above sea level, humidity, atmospheric pollution, requirements of shock protection, fire safety, etc.

4. Drive type, operation and control methods have to be determined according to the operating needs. Operation and drive of the unit needs an appropriate energy source, the existence of which has to be verified during device selection. Special needs regarding the control have to be considered.

5. Requirements of automatic protective measures are to be met, regarding the primary releases, the operating sequence during auto-reclosing, the selectivity of fuses, etc.

6. It has to be considered if further tests are necessary after installation and mandatory inspections (e.g. investigation of breaking inductive currents).
6. fejezet - Structure and operation of electrical switching devices

What we have learnt in the previous chapters provides a base for understanding the specifics of switching devices. We will discuss the unique features and selection methods of the different device types. First of all, we try to focus on practical aspects, making comprehension easier and we try to give an extensive overview of the field.

In the previous five chapters, we have reviewed the tasks and applications of the LV, MV, and HV switching devices used in electric power systems. We have presented the most important electrical, thermal and mechanical transient processes that can occur during closing and opening mechanical switching devices. We have analyzed the effect of the electric arc appearing during switch-offs. Finally, we have discussed some general rules of device selection.

All electrical switching devices consist of similar components, like contacts, electromagnets, LV arc quenching units, bimetallic thermal releases, latching mechanisms, etc. Contacts and electromagnets are part of both HV and LV equipment, and they are used also in the arc control devices of LV units, like blow-out coils deflecting the arc into a chute. We devote more attention to a particular arc chute, the deion plates.

![Fig. 6.1. a); b); Arc chutes with deion plates](image)

The arc entering the deion plates splits into several parts. All the short arcs connected in series have their own anode and cathode drops, and their sum results in a significantly raised arc voltage. Deion plates can multiply $U_{ak}$ yet with a single contact point (Fig. 6.1), although its effect can be exploited with two contact pairs as well (Fig. 6.2). This type of arcing chamber consists of insulated copper or iron plates. In case of iron, the metal is covered by a thin copper or silver layer. To obtain as large $V_{opt}$ as possible (see formula (2-10)), an optimal distance (0.3...1.0 mm) should be kept between the adjacent plates. An additional fortunate property of this arc chute type is the cooling effect of the relatively high metal masses. Cooling the arc spots results in intensified de-ionization. Iron adds another advantageous effect, namely the electro-dynamic contracting force pulls the arc into the chamber.

We begin the discussion of the electric switching devices with relays and releases, as they can be components of other units. We continue with the following AC devices in respective order: circuit breakers, fuses, disconnectors, load switches, device combinations, and overvoltage protection devices. We treat the special electric transients occurring during the operation of fuses in this chapter as well.

1. Relays and releases

Automatic protection systems ensure the safety of electric power transmission, distribution and consumer networks. The relays and releases are part of these systems; they can be stand-alone units, or replaceable or built-in elements of other switching devices (e.g. CB). Furthermore they can provide auxiliary protection, for instance with contactors. Their task is to continuously monitor different parameters of electrical systems or equipment. Based on the variation of these parameters they detect faults or other abnormal conditions, enable fault clearance, terminate abnormal conditions, and initiate signals or indications automatically without human interaction.
Without the details of the protective applications, we deal with the main properties, classification, structure, and operation of the relays and releases. Based on previous knowledge from other subjects, we focus only on the most important characteristics of these devices.

1.1. Properties, classification

In the following, we describe the main characteristic properties of the relays and releases:

1. **Monitoring capability**. They continuously monitor the variation of a physical – usually electrical – quantity on their input. If the measured parameter reaches a pre-set threshold, they come into action and response. They do not provide information about the measured momentary values, they can only indicate whether the measured quantity is above or below the threshold level.

![Fig. 6.1. Basic functional types of relays and releases](image)

1. Their **control capability** is a function that goes hand in hand with their response, and results in an instantaneous change in their output. Relays and releases can be distinguished according to their control capability. Relays provide a closing or opening contact that is, their output is an electrical signal, whereas releases exert a force that is, their output is mechanical. They response if the parameter (current, voltage, temperature, etc) they measure reaches a given value. Both device types can have similar inputs – e.g. electrical – but they are different in their outputs. The relay outputs are electrical as they close or open contacts, the releases trigger mechanical latching mechanisms. Measuring can be direct or indirect; for instance through a transducer, if the measured quantity is electrical. Accordingly, we distinguish primary and secondary relays and releases. These basic types (primary relay, secondary relay, primary release, secondary release) are demonstrated in Fig. 6.1 with electromagnet operated, current sensing relays and releases. They response to the current flowing in a circuit or to a current proportional with the circuit current. The releases trip the circuit directly, whereas the relays transmit a signal to a release, which will break the circuit. It is worthy of notice that the relays of Fig. 6.1, usually just trigger a more complex control chain including a special logic with time relays and auxiliary relays. At the end of this control chain, there is an operating relay that trips a release. Measuring relays can be current-, voltage-, power-, impedance-, and frequency-relays.

2. The error limit corresponding to their **accuracy class** is usually expressed as a percentage value of 1, 2, 5, and 10 %.

![Fig. 6.2. Hysteresis of relay operation](image)
1. **Resetting ratio** or **resetting percentage** can be given for relays only. It follows from the fact, that their operate \((x_o)\) and reset \((x_r)\) values are different. Fig. 6.2 illustrates the operating hysteresis of maximal relays (relays, with which the positive change of the measured value triggers operation). The resetting ratio of the relay:

\[
\text{resetting ratio} = \frac{x_r}{x_o},
\]

and the resetting percentage is resetting ratio expressed as a percentage.

We have seen that relays – and occasionally releases – can be classified on various ways:

1. according to their role in the protection system (protection, measuring, control),
2. according to input quantities (current, voltage, power, impedance, frequency, heat, magnetic field, etc.),
3. according to sensing method (primary and secondary),
4. according to their operating method and structure (electro-mechanic, magneto-mechanic, thermo-mechanic, electronic).

Today, the electrodynamic and induction relays belonging to the group of electromechanical relays are nearly entirely replaced by electronic relays; therefore we do not deal with these two types. Because of the limited size of this book, we have to omit the electronic relays too. We treat only the most common electromechanical, namely the electromagnetic relays and releases, and introduce the operation and the structure of magneto- and thermo-mechanical relays.

### 1.2. Electromagnetic relays and releases

The exciting current flowing in the coils or in the conductors encompassed by iron yokes of relays or releases generates an operating magnetic force or mechanical moment \(M_o\). This can be compared to the braking moment \(M_b\), or braking force given as a reference value. The relay or the release will trip, if the operating moment exceeds the braking moment that is

\[
M_o - M_b \geq 0.
\]

(6-1)

![Fig. 6.3. Variation of mechanical moments in electromagnetic relays and releases](image)
Structure and operation of electrical switching devices

Fig. 6.4. Electromagnetic relays

Depending on the operating principle and structure of the device, the moment $M_o$ may be represented by different characteristic curves. The value of $M_o$ usually increases during the motion from the initial position $\alpha_i$ to the end position $\alpha_e$. The braking moment $M_b$ is the sum of the moment of the restoring spring $M_r$ and with relays the opposing moment of the contacts or with releases the opposing moment of the tripping mechanism $M_c$. $M_c$ comes into effect at the moment of contact touching $\alpha_c$ when the moving part reaches the stationary part. A frictional component $M_f$ adds to these moments, as friction always exerts a force opposing the direction of motion. Fig. 6.3 a. shows the variation of the moments ($M_i$ in the direction of pull), indicating the moment accelerating the moving part ($\Delta M$). On the one hand, acting on the moving masses, $\Delta M$ determines the time of acceleration, on the other, it affects the resetting ratio. Larger the $\Delta M$ when the moving part is pulled in, higher is the deviation of the resetting ratio from one (considering the value of $M_b$ in the direction of reset). With protection relays, smaller $\Delta M$ the better. It is not relevant with auxiliary relays, because they have to remain steadily pulled even if the supply voltage decreases. Fig. 6.3.b shows the relations between the moments in case of operate and reset. The start of pull is indicated by $P$, and the start of reset by $R$. If the relays are used for voltage- or current sensing protection relays – in order to obtain a favorable, close to one resetting ratio – the characteristic curve of the electrical moment $M_o$ should be adjusted to make $\Delta M$ as small as possible in the pulled-in state. The favorable characteristics can be achieved by adjusting the shape of the air gap, or the magnetic saturation of the armour. In Fig. 6.3.b, dashed line shows the modified characteristic curve $M_o'$. It can be clearly seen that $\Delta M = \Delta M'$ in this case. The sketch of a similar protection relay with a thin, saturating, “Z” shaped rotating armature can be observed in Fig. 6.4.a, where 1. indicates the yoke, 2. the rotating part and armature, 3. the exciting coil, and 4. the contacts. As electromagnetic relays are also used as auxiliary relays, we show the sketch of such a unit with tilting armature in Fig. 6.4.b (the numbers have the same meaning as in Fig. 6.4.a).

Fig. 6.5. Electromagnetic releases
The electromagnetic primary (short-circuit or instantaneous) releases are small electromagnets in which the coil is energized by the current of the circuit to be protected. The magnetic flux exerts an attraction force on the moving part or armature, which is clamped to a spring providing a force against the magnetic attraction. Pre-stressing the spring makes available to set the operate current of the release, namely the smallest fault current that triggers the armature. The armature instantly trips the circuit by releasing a latching mechanism in the circuit breaker. Two types of instantaneous releases are illustrated in Fig. 6.5. The release in Fig. 6.5.a does not have any coil, the high current of the circuit provides enough magnetic flux in itself. The special structure of the release in Fig. 6.5.b allows a smooth variation of the pulling force during operation.

1.3. Magneto-mechanical relays

Reed relays belong to the category of magneto-mechanical relays. It is clear from Fig. 6.6 that these relays behave like the armature and spring together in an electromagnetic relay. Not only a separate spring, but also the exciting coil and the yoke of the electromagnet are missing from this device. Its simple structure consists of two resilient iron strips forming the contacts and sealed in a narrow glass tube. There is a small, some tenth of millimeters wide gap between the ends of the non-energized iron strips that is, between the open contacts. The contact points are plated with an arc resistant, low resistivity conducting layer. In case of DC or extra low voltage, the coating can be Ag, AgPa or Au. In devices used at 230 V, it is W or WAg. The glass tube might be filled with air, nitrogen, hydrogen or with a noble gas, sometimes there is vacuum inside.

The reed-relay can be operated by a static magnetic field, for instance from a permanent magnet of Fig. 6.6. The magnetic flux lines are closed through the iron strips and the contacts. If the magnetic field disappears – owing to the remanent flux – the contacts separate and the relay gets to normal state. The spring force of the strips is adjusted to make the switch-on and switch-off fast and reliable.

There are polarized reed relays as well, with varying sensitivity for the direction of the magnetic field. There are such devices, in which an integrated coil (solenoid) generates the static magnetic field. They belong to the group of electromagnetic relays, as their input is electrical.

1.4. Thermo-mechanical relays

The relays with temperature input belong to this category. The bimetallic strip operated relays, improperly called thermal relays, are not part of this group, since their input is electrical. From the numerous thermo-mechanical relays (used for instance in room thermostats), we discuss only the a) bi-metallic switch and b) the thermistor relay, both employed in electric motor protection.

1.4.1. Bimetallic switch

The operation principle of the bimetallic switch or thermal-driven micro relay can be observed in Fig. 6.7. The small (with a diameter about 8…15 mm), spherical cap shaped bimetal membrane is situated in a shell. If the temperature surpasses a pre-set limit, the membrane suddenly turns over, and breaks the protected the circuit.
1.4.2. Thermistor relay

An essential component of thermistor relays is their sensors, which are semiconducting, temperature-dependent resistors. We distinguish two thermistor types. The resistance of the negative thermal coefficient (NTC) thermistors decreases, whereas the resistance of the positive thermal coefficient (PTC) types increases with higher temperature. Fig. 6.8 plots the characteristics of PTC thermistors. The relay responses, when the temperature reaches a threshold $T_{\text{sense}}$, located on the steep slope of the curve. The resistance of the thermistor shall be $R \leq 550 \, \Omega$ at $T_{\text{sense}} - 5 \, ^\circ\text{C}$ and $R \geq 4000 \, \Omega$ at $T_{\text{sense}} + 15 \, ^\circ\text{C}$. This indicates that the gradient determining the reliability of the device, shall be at least 172.5 $\Omega/\circ\text{C}$ at the steep part of the curve.

![Fig. 6.8. Characteristic curve of a PTC thermistor](image)

![Fig. 6.9. Measuring block of a thermistor relay](image)

In case of three-phase motor protection, the thermistors are embedded into the stationary coils of the motor, and they are connected in series. Another element of the relay, a measuring unit, monitors the resistance variation. One variant of such a measuring block can be seen in Fig. 6.9. The electromagnet controlled reed relay $K$ is responsible for sensing and triggering the output. We note that if electronic components measured the resistance, the relay would belong to the group of the electronic instead of the thermo-mechanical types. The three PTC thermistors in series are connected to the terminals 1 and 2 of the measuring unit. The terminals 11 and 12 provide the connection of the output signal. The 230 V AC supply voltage necessary for operation is fed through the terminals $R$ and $M$. The transformer $P$ and the rectifier convert this to extra low voltage and galvanically separates it from the mains. The measuring circuit consisting of the thermistors, the adjusting resistances and the coil of the reed-relay takes the power from the output of the rectifier and the filter. The reed relay with low reset ratio cannot operate if the PTC is cooled, although it keeps the contacts closed after operation. The relay pulls in if we press the normally closed start button $V$. By pressing $V$, its contacts open, and at the same time a permanent magnet gets close to the reed relay, which pulls in. After releasing $V$, the reed relay remains in the closed position resulting in a shorted output. If the thermistor resistance reaches the threshold temperature $T_{\text{sense}}$, the current of the coil drops under the disengaging current and the output opens.

2. Circuit breakers

The high, medium, and low voltage circuit breakers (CB) are mechanical switching devices that can make or break currents during normal or fault (including short-circuit) conditions. Mechanical means that switching
operation is accomplished by separable opening or closing contacts. Furthermore, if their contacts are closed, CBs have to be able to conduct operating currents for an unlimited, and fault currents for a limited time.

As we began the discussion of switch-off transients with HV phenomena, it is also reasonable to treat HV circuit breakers first.

### 2.1. High voltage circuit breakers

We do not discuss in details the a) oil and b) air blast circuit breakers. As these two CB types are on the verge of extinction, we give only a short description about them:

1. **Oil circuit breakers (OCBs)** are circuit breakers that have their contacts immersed in insulating oil. Current interruption takes place in oil which cools the arc and thereby quenches the arc. The heat vaporizes the oil, resulting in a gas bubble around the arc. The pressure of the gas is proportional to the current intensity. Besides, higher the current more intense is the flow of the oil that is its cooling effect, and more powerful is the gas evolution, which detracts heat from the arc. Therefore, the arc quenching capability and the degree of ionization in the arc channel depend on the current to be interrupted. Consequently, oil circuit breakers are self-quenching types, and they are not prone to current chopping.

2. In **air blast circuit breakers**, the arc is extinguished by flowing air compressed to 10...30 bar pressure. In the volume between the contacts being separated the air flows with around the speed of sound; it cools the arc and drags one part of the charge carriers. The most important part of the arc quenching chamber is the Laval-nozzle, where the air is accelerated. The amount of air is independent from the current intensity, just like the arc quenching capability. The amount of air is tuned to rated breaking capacity, therefore current chopping occurs with low currents.

Two state-of-the-art CB types are prevalent today in HV and MV networks: c) **sulphur-hexafluoride** and d) **vacuum circuit breakers**. The principle of the latter one is used in MV contactors for motor switching as well, and we treat this vacuum type in more details here. The sulphur-hexafluoride type is the exclusive CB of HV systems, although it can be part of MV circuits as well. We provide only a short description of this CB:

1. Sulphur-hexafluoride (SF$_6$) is an odorless, not toxic, non-flammable, chemically stable gas up to 500 °C, its density in normal state is 5 times of the air and can be easily liquefied. It is an inert, heavy gas and its good dielectric and unequalled arc extinguishing properties made possible the development of SF$_6$ circuit breakers. In these devices, arc quenching occurs in a closed extinguishing chamber, where the gas continuously flows around the arc, or the arc moves in the SF$_6$. Regarding this motion, we can distinguish two classes of SF$_6$ circuit breakers: gas blow, and rotating arc types. The quenching mechanism in a blow type CB is similar to that of the air blast circuit breakers. The arc is surrounded by a Laval-nozzle, and is cooled and de-ionized by the axial flow of the high pressure (10...16 bar) gas. This quenching mechanism is independent or partly independent from the current, although not prone to current chopping. Rotating arc units are self-extinguishing, and the gas flow is perpendicular to the arc axis in them.

2. **vacuum circuit breakers**

Compared to other electrical insulators, vacuum (10$^{-5}$...10$^{-6}$Pa) – especially with small electrode distances – has very good insulation properties (Fig. 6.10). The decrease of gas pressure results in the growth of the mean free path of molecules and of free charge carriers to several times of the electrode distances. Theoretically, this excludes the possibility of a gas discharge. This condition is satisfied at a pressure of 10$^{-1}$ Pa. Nevertheless, breakdown can still occur, since the accelerated electrons hit the anode, where their kinetic energy vaporizes a microscopic part of the surface. The metal vapor leads to a discharge similar to gas discharges.
Vacuum arc consists of metal vapor plasma emitted from the anode and the cathode. The primary source of the charge carriers is thermal emission. Only radiation can transmit the generated heat from the arc, but its effect is small, resulting in high arc temperature, and low arc voltage (50...200 V). First, the cathode spot appears at contact separation. Approximately up to 1 mm field emission, at higher distances the electrode vapor is responsible for current conduction. By raising the current, the arc undergoes the following transitions:

1. With smaller currents, up to about 100...150 A, only one arc spot appears, and only at the surface of the cathode. Therefore, there is no anode drop. The pressure is about 10^5 Pa (1bar) inside the metal vapor plasma, and there is vacuum outside of it. The inner vapor pressure is balanced by the electrodynamic contracting force (Fig. 2.19). In case of AC current, the arc extinguishes prior to current zero, resulting in current chopping. Higher the current, less prone is the CB to current chopping, since the arc pressure rises with growing current. In case of high short-circuit currents, it might be even completely eliminated. In practice, the CB is considered prone to current chopping with a particular current intensity, if the probability of chopping is larger than 5%.

1. With larger currents, up to about 4 kA, more than one current filament appears between the electrodes, each carrying approximately 100...150 A. There is still no anode drop. Between 4 kA and 8...12 kA, the current filaments merge at the anode resulting in one anode spot, and anode drop appears. Around 8...12 kA, a concentrated spot appears at the cathode too.

With decreasing current, the transition takes place in a reverse order.

Since the arc plasma consists of metal vapor, the electrode material determines the properties of the arc. As a consequence, contacts must satisfy special conditions. The most important of these:

1. **Minimal susceptibility to current chopping**, high partial vapor pressure. The materials can be characterized by a mean current value that results in current chopping with the probability of 5%. For Cu, it is 4A, for Ag 6A, for W 9.2A, Sb (antimony) 0.5 A. With copper-chromium or silver-selenium alloys, used in MV circuit breakers, 2...5 A and 0.5...1 A was measured respectively.

2. **Low arc voltage** at AC, which results in less thermal stress. In case of Cu and Ag, the arc voltage is too high.

3. **Low material loss** (when interrupting less than 3 kA, the material transfer results even in the increase of the anode weight). There is neither oxidation nor convective heat transfer in vacuum; therefore plain, circular contacts can also be used. Experimental studies show that higher current raises, and higher contact diameter reduces contact erosion. With currents of 10 kA or more, the material loss with smooth circular surfaces would be too high, therefore the special structure of figures 6.11 and 6.12 are applied. The magnetic field of the radial component of the current path forces the arc to rotate between the ring surfaces of Fig. 6.11. Since the base point of the arc continuously moves, the arc does not burn at a single point, material loss is reduced, and durability increases. Similar result can be achieved with the contact structure of Fig. 6.12, where the force from the axial magnetic field component results in a diffuse arc, uniformly stressing the surfaces.
1. *Low susceptibility to welding*. Oxide tarnish cannot develop on the surface of metals in vacuum, therefore the contact surfaces easily bond together and weld. This makes their separation harder, resulting in ragged and ruptured surfaces at the previously bonded points. However, rough and sharp edges significantly worsen the dielectric strength. To avoid this, contacts are made from two-component alloys, like Cu-Bi or Ag-Pb.

2. *Gas-free materials*. Gas content of 0.1 ppm is allowed, what can be achieved only with complex technologies (de-oxidization with phosphorus, melting in vacuum, zone induction melting). The remaining gas can be bound with gettering agents, like Zr used in the temperature range of 1100...1700 °C. The cold getter effect of Pa can be exploited for the manufacturing of the screens against condensed metal vapor.
The structure of a rotating arc vacuum chamber can be seen in Fig. 6.13. The insulators (6) are usually made from special metal-oxide ceramics which make the joints to the metal fittings available to seal vacuum. The stationary contact (1) is fixed to one end of the chamber, and the operating and connecting bolt (3) is connected to the moving contact (2) through a pipe membrane (4) and a guide. The thin membrane plays the role of sealing the moving contact, and its service life is improved by a screen against the condensing metal droplets. The high vacuum is accomplished by aspiration to 10…30 hours at a temperature of 200...500 °C. With this technology, the vacuum remains in the chamber to several decades. If the chamber is out of service for a longer time, the weakened vacuum can regenerate after some low current interruptions. Vacuum chambers are applied mostly in MV networks, although units for more than 100 kV have already been constructed.

An advantage of the closed vacuum chamber is its possible application in environments with fire and explosion risk. The current usually breaks at the first zero. Thus, the short arcing time results in long life time. Besides, the short arc and low arc energy contribute to the durability of the chamber as well. The small contact distance and low energy need for operation makes the use of simple electromagnetic drives available.

Fig. 6.14. MV, spring driven vacuum circuit breaker

Fig. 6.14. shows a MV vacuum circuit breaker. The three poles have a common drive operated by a spring. These units are usually built on a carriage in air insulated switchgears, although there are solutions, when the vacuum chamber is situated in a closed SF₆ filled volume. The long service life and electromagnetic operation makes the vacuum chamber a perfect solution for MV contactors, for instance for switching motor currents. The motors however, must be equipped with overvoltage protection, since the coil insulation is sensitive to overvoltages generated by current chopping and possible re-strikes.

**2.2. Low voltage circuit breaker**
There are both AC and DC circuit breakers in low voltage systems. In case of AC, the maximum rated voltage is $V_r = 1000\, \text{V}$, in case of DC, it is maximum $V_r = 1200\, \text{V}$. There are LV CB-s with rated currents up to $I_r = 6.3\, \text{kA}$, their current breaking capacity can reach even $I_{sc} = 200\, \text{kA}$. These are the most expensive switching devices in LV networks, and their most important application is fault and overload protection (automatic disconnection). Frequent operation is not typical with these devices, no more than $c = 1 \ldots 5$ switching cycles are expected from them per day. To switch operating currents, manual load switches or contactors – equipped with protection against overloads – are used. They have to withstand the dynamic and thermal stress of short-circuit currents until the CB disconnects the fault. Another important requirement is the minimum $10^4$ mechanical and at least $10^3$ electrical switching cycles during their lifetime.

The function of the CB determines its structure and operation. We can distinguish three different basic types: general purpose (B type), current limiting (A type) and miniature circuit breakers (MCB). Before we treat the unique features of these types, we discuss their common structural – mechanical or electrical – elements. Finally, we introduce the reader to the selection of these devices.

### 2.2.1. Structural elements

Fig. 6.15 illustrates the elements of LV AC circuit breakers capable of synchronous switching of three phases together. The structural elements can be classified into four basic groups: current path, shunt releases, auxiliary contacts, mechanical elements. All of these can consist of replaceable or fixed components, but not all of them are part of the different CB types. For instance, DC circuit breakers have only two poles. We note that the real placement of the elements (shape of current path, placement of connecting terminals, etc.) is different from the location of the symbols in the figure, which provides only a clear illustration.

**The current path** (1) contains the connection terminals (2), the main contacts (3), the arc chute (4) including the arcing contact, possibly a release (5) and the fixed or flexible connections (6) between these elements.

1. **The connection terminals** (2) are usually bolted clamps for wires at smaller rated currents (up to $I_r = 160\, \text{A}$). With higher currents, the terminals are flat bars with through-bolts (usually with one hole for $I_r = 200-630\, \text{A}$, two holes for $630-1000\, \text{A}$, and four bolts for $1000-6300\, \text{A}$). Up to $630\, \text{A}$, the connection is usually made with cable clamps, above $630\, \text{A}$ the terminals are fixed to busbars. The material of the terminals is Cu.

2. Appropriate contact pressure (also in case of fault currents), minimal bouncing during closing, fast opening, effective arc quenching must be ensured for the **main contacts** (3). The importance of these requirements is different with different CB types. Besides, the electrodynamic force acting on the arc and the contact members also influences the contact arrangements. We will demonstrate the structure of such contact systems together with the discussion of the unique CB properties. With higher rated currents, the current path includes 2…4 parallel connected contacts. The material of the main contacts depends also on the fault current magnitude. Up to $3\, \text{kA}$ AgCdO, or AgZnO, up to $20\, \text{kA}$ AgW or AgNi and AgC asymmetric contact pairs. If **arching contact** is part of the current path, (with fault currents higher than $15\, \text{kA}$), then the main contacts are made Ag, AgNi or AgCdO, and the arcing contacts from AgW or CuW.

3. With AC LV circuit breakers, the **arc chute** (4) is composed of deion plates, whereas with DC devices, the method of constraining the arc into a narrow gap between insulators is also used. The arc control device is surrounded by a heat resistant (e.g. ceramics) enclosure. The magnetic field of the current path blows the arc into the arc chute, sometimes with the help of iron yokes or blow-out coils.
4. If the protection is not electronic, then the thermal-magnetic release (5) forms a serial element of the current path. In case of electronic protection, a current transformer or transducer replaces the releases, and the conductor of the current path forms its primary coil. The releases can be a directly or indirectly heated bimetallic overload release s (7) and/or an electromagnet operated short-circuit or fast tripping release s (8). The overload and the fast tripping releases are often integrated into a single (sometimes replaceable) unit forming a release combination. The overload release is direct, if the bimetallic strip is part of the current path and the current heats it directly. This solution is used with smaller rated currents (I≤63 A). With higher currents, the overload release is always indirect that is, a current transformer provides the current that heats the bimetallic strip. The response time of these releases depends on the current intensity.

The electromagnet operated fast tripping release is a small sized electromagnet. Its coil is part of the current path, and the magnetic force generated by the current pulls the moving part against a spring, and releases a latching mechanism. If the circuit breaker is capable of time discrimination, the fast tripping release can be delayed. In this case, an instantaneous release is also included in circuit breakers with high rated currents. Above a specific current limit, no delay is allowed: the instantaneous release trips the circuit instantly. Accordingly, the mass of the moving part must be small and the spring force must be strong in the electromagnet.

1. The connections (6) between these elements are provided by copper conductors. The flexible connections are made from thin, twisted threads or from bundles of thin strips.

Besides the releases fixed in the current path, there are also voltage operated releases (9) in LV circuit breakers. We discuss the properties of the solenoid operated shunt release (10) and undervoltage release (11) here.

1. Shunt releases are solenoids that actuate a tripping mechanism when a voltage is applied to them. When de-energized, the system is in its rest position. Shunt releases are used for remote tripping when an interruption in the voltage is not intended to lead to automatic disconnection. Tripping does not occur in the event of wire breakage, loose contacts or undervoltage. The release must provide reliable operation in the voltage range of (0.8 ... 1.2)·Vr.

2. Undervoltage releases are solenoids that actuate a tripping mechanism if the voltage drops under (0.4...0.6)·Vr. The system is in the rest position when energized. If the voltage is above 0.8·Vr, the release will reset making possible the closing of the CB. Undervoltage releases are always designed for uninterrupted operation. They trip the circuit-breaker when the power fails in order, for example, to prevent motors from restarting automatically. They are also suitable for very reliable interlocking and remote switch-off, since disconnection always occurs in the event of a fault (e.g. wire breakage in the control circuit). The CB cannot be closed when the undervoltage releases are de-energized.

Auxiliary contacts (12) provide command or signal outputs from processes which are governed by the position of the CB contacts. They can be used for interlocking with other switches, and for the remote indication of the switching state. Usually, they are in mechanical connection with the operating shaft of the main contacts.

The frame (13) and the operating mechanism belong to the mechanical CB elements.

1. The operating mechanism is mounted on the CB frame. The operation is provided by a mechanism driving the poles via a shaft, and a latching mechanism, which ensures the closed position of the contacts. Furthermore, the frame provides room for all the other components, and the frame makes possible the mounting of the CB into a switchgear or on a switchboard. The frame is usually made of metal. However, the advances in plastics technology made possible to replace the metal frame by plastic up to I=.1000 A (Molded Case circuit Breaker, MCCB).

2. The operating drive forms a part of the operating mechanism. A spring provides the driving force of the operating drive, which closes or opens the contacts with appropriate speed. The moving contacts are fixed to a shaft, and the rotating motion of this shaft moves the contacts. Latch and operating mechanisms are constructed regarding this rotating motion.

2.2.2. General purpose circuit breakers

The general purpose (B-type) circuit breakers are relatively slow, they do not need high switching speed and force, therefore the size of their drives can be smaller and their mechanical life can be longer. The thermal and
dynamic effects of the prospective short-circuit current ($i_s$) peak (Fig. 2.26) stress the general purpose AC circuit breakers and the network they protect. This fact has to be considered during the CB selection and the network design. The contacts of these devices open relatively slowly, even if no delay is set, usually no sooner than 5 ms after fault occurrence. The arc voltage slowly grows, and usually it does not reach the momentary value of the supply voltage. Consequently their fault clearing time is $t_f = 10...25$ ms. These devices are applied upstream of the low voltage network, close to the supply, where the largest rated and fault currents can be expected, and where the continuity of power supply is especially important. They have to provide protection for high current equipment, although they have to remain closed if the fault occurs farther from their location and can be cleared by another, downstream CB. In this case, a time delay of 100...500 ms has to be set for the fast tripping release to provide time discrimination. This implies that the prospective short-circuit current might flow in the circuit through several cycles, indicating a significant – mostly thermal – stress for the network.

![Diagram of a general purpose LV circuit breaker](image)

**Fig. 6.16. General purpose LV circuit breaker**

Fig. 6.16 shows the main structural components of a general purpose, metal framed, LV CB. (The illustration shows an old CB type, although it can be considered a classical example.) Thick line indicates the current path between the upper and lower connection terminals. The current path includes the main contacts between a fixed bar and a flexible stranded wire and the overload protective release, which is an electromechanical type in this case. A pair of main and a pair of arcing contacts belong to each phase. After contact separation, the arc appears between the arcing contacts and is drawn into the arcing chamber. A disadvantage of this construction is that the electrodynamic force acting on the closed contact tries to separate the contacts (expanding current loop). Therefore, the compressing force acting on the contacts gets smaller, leading to increased thermal stress, and possible welding. The conductor in the thermal-magnetic release passes through the yoke of the electromagnetic fast tripping unit and through the yoke of the current transformer, which heats the bimetallic strip of the overload release. Any of the releases automatically trips the CB by moving a lever that releases the latch of the switch-off spring. The threshold currents of the releases can be adjusted with rotary switches. Their theoretical overcurrent trip curve can be seen in Fig. 6.17, and it consists of two distinct sections. If the current is smaller than the short-circuit trip current setting ($I_{nm}$) and higher than the lower limiting current $I_l$, which in this case is equal to the rated current $I_r$, then the overload release will trip the CB with a delay depending on the current magnitude. If the current exceeds $I_{nm}$, the fast tripping release will trip the CB practically without a delay, and the main contacts open within 5-10 ms. Two typical ratios can be defined for the overcurrent characteristics. One of them is the thermal release rate:

$$R_t = \frac{I_t}{I_r},$$

(6-1)
Fig. 6.17. Characteristic tripping curve of overcurrent releases

where $I_l$ is the lower limiting current and $I_r$ is the rated current. The value of this ratio is close to one, in practice, $R_{f} = 1.1$ is usual. The other ratio is the fast tripping rate:

$$R_{t_f} = \frac{I_r}{I_l},$$

(6-2)

which, depending on the function of the CB, can be in the range of $R_{t_f} = 2...15$.

To raise the short-circuit breaking capacity (dynamic and thermal) of general purpose circuit breakers, the electrodynamic load bearing capacity of the main contacts has to be increased. To improve this property, special constructions are used in contact systems. The principle is to compensate the contact constriction force $F_c$ by the force from the current loop $F_l$. A generally used solution of this „balancing” principle is illustrated in Fig. 6.18. The moving contact is asymmetrically fixed to a pivoting point. This construction lets almost half ($F_l/2$) of the repulsive force emanating from the loop to act against the constriction force $F_c$.

Fig. 6.18. Contact construction with compensating forces on the moving contact

The sketch of a CB with excellent electrodynamic stress withstand capability equipped with “balanced” contact system is shown in Fig. 6.19. It is clear, that the contact system highly determines the structure of this CB, especially the shape of the current path without releases and the placement of the terminals. All structural elements – like current transformer at the lower terminal supplying the electronic release, the deion plate arc chute, the arcing horn – are aligned to the contact system. The rated current of this CB type is in the range of $I_r = 0.8...6.3$ kA, its short-circuit breaking capacity is between $I_{sc} = 50...150$ kA.

Fig. 6.19. State-of-the-art, general purpose, LV CB
2.2.3. Current limiting circuit breakers

The contacts of current limiting (A-type) circuit breakers open soon after occurrence of the AC prospective short-circuit current $i_F$. The arc voltage $v_{arc}$ increases rapidly and surpasses the supply voltage $v$ in a short time. Consequently, the peak of the current flowing through the CB (the let-through current, $I_{lt}$) can be significantly smaller than the peak ($I_{nm}$) of the prospective short-circuit current. Their fault clearing time is short, $t_{fc} \leq 5$ ms, and they limit the current peak (see Fig. 2.27). The conditions of current limitation are the followings:

1. The contacts shall open as soon as possible after current initiation.

2. Possible fastest increase of the arc voltage to exceed the value of $v_{arc} = v - I_{lt} \cdot R$ in the possible shortest time, where $R$ is the resistance of the fault circuit.

3. The high arc voltage has to be kept until the next current zero of the decreasing current.

The thermal and dynamic stress is much smaller than with general purpose circuit breakers, not to mention the reduced magnetic field. Therefore, during CB selection and network design, it is enough to take into account the let-through current and the real shape of the current flowing through the circuit. Fast operation can be achieved by the small mass and simple structure of the moving components, which are also stressed only by the let-through current. To separate the contacts fast and with a high speed, the electrodynamic forces of the current loops, or the pressure rise of air generated by the heat of the arc are exploited. Furthermore, after the contacts open, the electrodynamic force from the contact system must draw the arc into the arc chute as fast as possible. Delay of contact separation is very much limited, since it leads to the decrease, or possible complete elimination of current limitation that is, to the growing stress of the CB and of the equipment it protects.

The operation of “repulsive” contact systems applied in current limiting circuit breakers can be seen in figures 6.20.a….f. The force acting on the moving contact and the arc can be raised with U shaped iron yokes, as seen in figures 6.20.d….f.

![Diagram of current limiting circuit breakers](image)

**Fig. 6.20. ábra. Áramkorlátozó megszakítókban alkalmazott taszító érintkezőrendszerek**

1. Drawing a. shows a contact system with a single current loop generating a repulsive force.

2. With the double loop of drawing b, the repulsive force can be further increased. Besides, this solution provides double contact points.

3. In drawing c, a striking magnet is series connected into the current path. This magnet does not act on the arc, its only role is to help to open the contact above a specific current by striking the accelerating contact member after it has opened.
4. In drawing d, the “pulling type” U shaped iron yoke helps to raise the opening force on a single contact.

5. In drawing e, the “pushing type” U shaped iron yoke increases the repulsive force acting on a single contact.

6. The unique solution in drawing f, exploits the force acting on current $i_2$ induced in a special loop forming the moving contacts. This current is proportional to the fault current gradient ($\frac{di_2}{dt}$). The repulsive force is further increased by a U shaped iron yoke. This construction is extremely effective when very high fault currents, namely currents with steep slope are to be interrupted.

Figure 6.21 shows a single looped contact system (see Fig. 6.20) combined with a special release mechanism. The elongated fixed (1) and moving (2) contacts help to increase the repulsive force acting on the loop carrying a fault current. The contact members touch in point c, they are in closed position. The claw (4) of the moving contact (2) leans to the axle shaft of the release, its arm together with a lever (3) to the hinge (b). The force of overload or small short-circuit currents is not enough to operate the mechanism. In these cases, traditional tripping mechanisms rotate the axle shaft and open the contacts. With high currents however, the electrodynamic force of the loop is sufficient to shift the hinge (b) into the direction of the arrow, and the claw (4) of the moving contact (2) rises above the shaft (before it could turn). Finally the spring and the electrodynamic forces rapidly separate the contacts. This results in the fast growth of the arc length and finally the arc is drawn into the arc chute. A practical solution of a similar electrodynamic latching mechanism is shown in the section view of a current limiting CB in Fig. 6.22.

![Fig. 6.21. Single looped contact system combined with a special release mechanism](image)

Fig. 6.22. Current limiting CB with a contact system similar to Fig 6.21.

Fig. 6.23 shows the axonometric view of a current limiting MCCB with single, repulsive contact loop similar to the contact system of Fig. 6.20. The meaning of the numbers in the figure: 1. upper terminal, 2. deion plates, 3. moving main contact, 4. fixed main contact, 5. spring operating mechanism, 6. rotary switch for setting the overload release, 7. release unit including thermal and fast tripping mechanisms, 8. rotary switch for setting the fast tripping current, 9. release indication, 10. operating handle.
The current limiting compact CB in Fig. 6.24 has especially high breaking capacity. Each of its poles is situated in a separate enclosure with two contact pairs in their current path. The moving contacts are fixed to a rotating shaft and the current is interrupted at two points, doubling the arc voltage. The contact system is similar to the one in Fig. 6.20.e: a U shaped yoke amplifies the repulsive force acting on the single looped contacts. Another technology is added to this interruption method to further increase current breaking capacity. This technology exploits the pressure growth generated by the heat of the arc (see Fig. 6.25). The energy of the arc, namely the pressure growth is transmitted via a piston to a spring mechanism, which trips the CB approximately 3 ms after the contacts has opened, if the prospective fault current exceeds a threshold (around $I_r \approx 25 \cdot I_r$). Under this threshold, the pressure is not enough to open the contacts, only the effect of the increased arc voltage limits the current. Above the threshold, current limitation is further improved, the interruption takes place after around 1 ms. The rated current of these devices is in the range of $I_r = 100...630$ A, and their short-circuit current breaking capacity is $I_{SC} = 20...100$ kA. All circuit breakers of this manufacturing series can be equipped with electronic release, although up to $I_r = 250$ A, thermal-magnetic release can also be applied.

### 2.2.4. Miniature circuit breakers (MCB)

Miniature circuit breakers (MCB) form a special group of LV circuit breakers, not only because of their small size and easy installation, but mainly due to their small rated currents ($I_r = 4...125$ A) combined with high breaking capacity ($I_{SC} = 3...25$ kA). The high fault breaking capacity is related to their current limiting behavior resulting from their small size, and mass, their fast operation, and their arc chute, which raises the arc voltage extremely rapidly. They are essential components of low current consumer circuits. Their manual operation
makes possible the switching on or off load currents. Furthermore, a bi-metallic overload release and a magnetic fast tripping release are serial elements of their current path, ensuring protection against both overload and short-circuit currents. This function and the possibility of their repeated operation (their mechanical durability reach up to $2 \times 10^4$ sc) make them an ideal replacement of fuses in consumer circuits. Fuses can remain as a secondary protection upstream, at the supply. Owing to the mass production, miniature circuit breakers are relatively cheap. They are compact, their structural elements are enclosed in a closed plastic housing.

Fig. 6.26. Structure and operation scheme of an MCB

The outline of MCB structure and the operating scheme of the overcurrent protection is shown in Fig. 6.26. The fast tripping release is a solenoid type AC electromagnet inserted into the current path. If energized, its moving part releases a latch of the spring operated drive. When bends, the bimetallic strip heated directly operates the same latch. Both the structure and the operating principle of overcurrent releases in MCBs are similar to those in other CB types. The difference is that in MCBs, threshold levels are fixed. Therefore the characteristic overcurrent protective curves of MCBs are identical with the characteristics in Fig. 6.17. There are different protective functions, for which MCBs can be used. Regarding these functions, devices with three distinct, standardized characteristics are available on the market, denoted by the letters B, C, and D. These curves differ in the lower limit of the fast tripping current range, as it can be clearly seen in the diagrams of Fig. 6.27. Characteristic B ($R_{lt} = 3...5$) is recommended for the protection of wiring, curve C ($R_{lt} = 5...10$) for general household purposes, and curve D ($R_{lt} = 10...20$) for motor protection.

Fig. 6.27. Standard MCB characteristic tripping curves
The behavior of MCBs during fault current interruption can be characterized by their let-through energies that is, by the operating Joule-integral \( I^2 t \). The let-through energies for MCBs with different rated currents are plotted in Fig. 6.28 as function of the rms value of the prospective fault current \( I_F \). It can be seen that, for instance an MCB with \( I_r = 25 \text{ A} \) lets through only 7.5 % of the energy of an \( I_F = 4 \text{ kA} \) sine half wave, and an MCB with \( I_r = 100 \text{ A} \) around 6.6 % of an \( I_F = 15 \text{ kA} \) sine half wave.

2.2.5. Selection

The general rules of switching device selection (see chapter 5) are valid for MCB selection as well. We have to determine and verify the mechanical and electrical properties of the device, the installation and ambient conditions, the requirements for the operating drive and control, and the requirements of protection. To satisfy the requirements of protection – with general purpose circuit breakers – we have to verify, if the conditions of selectivity are satisfied among the protective devices of the network. Selectivity or discrimination means that only the protective device closer to the fault or overload has to disconnect the circuit. To achieve selective operation, the characteristic curves of the circuit breakers have to be coordinated.

Selective operation of overload releases can be guaranteed only, if the tripping curves of the serial devices do not overlap. In practice, this condition can be fulfilled, if the relations \( I_{mdw} \leq I_{scdown} \) and \( I_{mbox} I_{mboxdown} \) can be granted for the tripping curves of the upstream and downstream protective devices (see Fig. 6.17). The latter criteria is a necessary (but not sufficient!) condition of selective operation, therefore other requirements have to be satisfied as well.

In the extended network of Fig 6.29.a, current discrimination of the fast tripping releases can be realized. Due to the impedance of the 150 m long cable connecting the circuit breakers CB1 and CB2 at the supply and at the final circuit respectively, the terminal fault currents at the two CBs significantly differ. The short-circuit current is much smaller at the downstream CB2: \( I_{scdown} = 10 \text{ kA} \) at CB1, whereas \( I_{scdown} = 5.9 \text{ kA} \) at CB2. Similarly, the 20 m long wire of the final, motor circuit reduces the short-circuit current at the motor to \( I_{sc} \). To ensure current discrimination, the characteristic curves of the protection system have to satisfy the following conditions (see Fig. 6.29.b):

1. The smallest short-circuit current \( I_{scdown} \) of the downstream CB2 has to be higher than the fast tripping current \( I_{scup} \) of the same CB2 (\( I_{scdown} > I_{scup} \)). In the example of Fig. 6.29, this condition is fulfilled, as \( I_{scdown} = 4 \text{ kA} \) and \( I_{scup} = 1 \text{ kA} \).

2. The highest short-circuit current (terminal fault) of the downstream CB2 has to be smaller – with appropriate safety – than the fast tripping current \( I_{scup} \) of the upstream CB1 (\( I_{scdown} > I_{scup} \)). This condition is also satisfied in the investigated case: \( I_{scdown} = 5.9 \text{ kA} \) and \( I_{scup} = 6 \text{ kA} \).

3. The terminal fault current \( I_{scup} \) of the upstream CB1 has to be higher than the fast tripping current \( I_{scup} \) of the same CB1 (\( I_{scup} > I_{scup} \)). This condition is fulfilled, as \( I_{scup} = 10 \text{ kA} \) and \( I_{scup} = 6 \text{ kA} \).
4. In the current range of $I_{\text{SCmax}}=I_{\text{SCdw}}I_{n_{\text{op}}}$, the overload release of the upstream device CB1 trips the circuit with a delay corresponding to its characteristic curve. In our case, the disconnection time in the range of $I_{\text{SCmax}}=5.9I_{z}I_{n_{\text{op}}}=6 \text{ kA}$ (indicated by hatching in Fig. 6.29.b) is $0.9...8 \text{ s}$.

Fig. 6.29. Current discrimination with general purpose circuit breakers

The network of Fig. 6.30.a is not appropriate for current discrimination, because the low serial impedance of the connecting lines do not reduce enough the short-circuit current downstream of the supply. Selective fault tripping can be accomplished only by time discrimination. As the tripping diagrams in Fig. 26.b show, the following conditions are fulfilled in this case:

1. The fast tripping times of CB2 and CB1 are delayed by 150 and 300 ms respectively, whereas the short-circuit tripping of CB3 is instantaneous.

2. CB1 is equipped with an instantaneous tripping mechanism that does not allow a delay, if the current exceeds an upper limit of 20 kA. This threshold is higher than the terminal fault current at CB2 (18 kA). This solution provides also current discrimination in the current range of $I_{z}=20...24 \text{ kA}$.
Structure and operation of electrical switching devices

Fig. 6.30. Time discrimination with general purpose circuit breakers

Usually, neither current nor time discrimination can solve the selective fault protection of an AC network equipped only with current limiting circuit breakers. This is the case with MCBs as well, which are current limiting too. To ensure selectivity, other techniques have to be applied, like the three methods we discuss below:

1. Selectivity can be achieved with fast auto reclosing. After interrupting the short-circuit current occurred in the final circuit, the CB at the supply recloses e.g. two times and the CB downstream from the supply, but upstream from the point of the fault recloses once. The CB at the final circuit does not try to close again. Finally, only the faulty section is disconnected from the network. In this system, only circuit breakers with fast reclosing capability can be used, which devices are exposed to increased electrical and mechanical stresses. A further disadvantage of this method is that, although only for a short time, healthy parts of the system are also disconnected.

2. In systems capable of logic discrimination, the serial (both general purpose or current limiting) circuit breakers are equipped with specially designed electronic trip units. A pilot wire connects in cascading form the protection devices of the installation and transmits information between them (Fig. 6.31). When there are no downstream faults, the electronic units receive a low level input. In this standby mode, the time delay of the protection function is reduced ($t \leq 0.1$ s), and the electronics does not transmit any orders. When a fault occurs, each circuit-breaker upstream of the fault (detecting a fault) sends an interlocking order (high level output) and moves the upstream circuit-breaker to its natural time delay (high level input). The circuit breaker placed just above the fault does not receive any orders (low level input) and thus trips almost instantaneously. Accordingly, all circuit breakers detect the fault occurring at the point indicated in Fig. 6.31, and by changing to high level output, they send an order to the electronic unit of the CBs upstream. This sets the upstream CBs to their own delay time. Since CB3 closest to the fault does not receive any order (low level input), only this unit trips almost instantaneously. The operating time of this unit is shorter than the
delay time of the upstream devices; therefore the upstream CBs remain open. This logic discrimination method – with which all circuit breakers operate practically immediately – is widely used in the USA.

![Cascading, time functions](image)

1. Finally, we discuss the selective fault operation of current limiting circuit breakers with reflex releases, and the method of **cascading**. Cascading is the use of the current limiting capacity of circuit breakers at a given point to permit installation of lower-rated and therefore lower-cost circuit breakers downstream. The upstream circuit breaker acts as a barrier against short-circuit currents. In this way, downstream circuit breakers with lower breaking capacities than the prospective short-circuit (at their point of installation) operate under their normal breaking conditions. Since the current is limited throughout the circuit controlled by the limiting circuit breaker, cascading applies to all switchgears downstream. It is not restricted to two consecutive devices. Let us consider the circuit breakers CB1 and CB2 in the system of Fig. 6.32. If the rated current of CB1 is at least two times of the rated current belonging to CB2, and a high fault current occurs, then the contacts of CB2 open first at the moment of \( t_2 \). The arc voltage \( v_{arc2} \) across the contacts significantly reduces the gradient of the prospective short-circuit current \( i_F \). By detecting this reduced current, the contacts of CB1 open at the moment of \( t_1 \), although the energy of the arc voltage \( v_{arc1} \) across its contacts is not enough for a pressure growth \( p \), that could trip the reflex release. Therefore the contacts of CB1 close at the moment of \( t_{1c} \). In the time range of \( t_1 \ldots t_{1c} \), however, the arc voltage \( v_{arc1} \) is added to voltage \( v_{arc2} \) and helps, by additional limitation and reduced arcing time, circuit-breaker CB2 to open. Eventually the breaking capacity of CB2 is enhanced by coordination.

3. Fuses

The **low and medium voltage fuses** are electrical switching devices that automatically interrupt excessive currents lasting for a specific time by melting one or more metal wires or strips connected parallel (fuse element) inside a fuse link and quenching the electric arc, which occurs after melting. The fuse element has a relatively small cross sectional area, thus it can be considered as an intentionally weakened point of the electrical network. Its fault clearing time (the time between fault occurrence and final arc extinction) in case of short-circuits is a fraction of the half cycle in AC systems. In case of overloads, the disconnection time can be much longer; it can be even of the order of hours.

The fuse has two functions: first, it provides protection against short circuits and limited protection against overload currents. Second, it has to be able to conduct rated or less than rated currents for an unlimited time. Consequently, the function of the fuse is similar to that of the CB, but providing automatic interruption only once. It is a protective device in the electric power system.

The fuses can be classified on different ways. As their most important task is fault protection, their primary classification is based on their **operation during short-circuits**. We can distinguish current limiting and non-current-limiting types. If the fuse is not current limiting, the fuse element melts only after the peak of the prospective current. The operation of current limiting types is much more fortunate, because their fuse element...
melts before the prospective peak. Current limiting fuses are more widely used; therefore, we deal only with this type here, omitting the attribute “current limiting” in our discussion.

Another aspect of classification is the **rated voltage**. Fuses are used only at low and medium voltages. The problems evoking at higher voltages make their application unfeasible. Owing to their limited (mainly longitudinal) size and their structure, the short-circuit current breaking capacity of MV fuses strongly decreases with increasing voltage (in the specified range). Besides, their current limiting capability is less powerful with higher rated currents. For instance, the highest rated current of an MV fuse is $I_r = 100$ A at $V_r = 7.2$ kV, which corresponds to a current breaking capacity of $I_{SC} = 50$ kA. If $V_r = 40.5$ kV however, then the maximum rated current is only $I_r = 25$ A with a current breaking capacity of merely $I_{SC} = 10$ kA. These problems usually do not exist or they are of less importance with low voltage fuses. The biggest problem with LV fuses is to raise their rated current belonging to an appropriately high current breaking capacity (even $I_{SC} = 100$ kA). They generate significant loss, namely heat, which has to be transferred away, limiting the size of the device. For instance a loss of $P = 90$ W is produced in a fuse link with a rated current of $I_r = 1250$ A. The maximum rated current of LV fuses is $I_r = 1600$ A.

Classification regarding the **structure and characteristic tripping curves** is reasonable only with LV fuses. These can be grouped as D-type (end contact or screw type), blade type (NH type), and cylindrical-cap-contact fuses, with partial range or full range characteristics that can be fast, ultra fast, delayed (slow) or combined (slow-fast).

1. Although the structures of MV and LV fuses are substantially different, the basics of their operating principle are the same. In the section devoted to MV fuses, we explain the common features of MV and LV units as well. During the discussion of the LV fuses, we deal only with the specific properties resulting from their dissimilar structure and different time-current characteristics. We treat the selection of LV fuses only, since the problems related to selection arise mostly in LV systems.

### 3.1. Medium voltage fuses

We treat MV fuses in three subsections: operation during short-circuits, operation during overloads and structure.

#### 3.1.1. Short-circuit operation

The fastest temperature rise of the fuse element can be expected, if the current does not have a DC component (see section 2.1.1). In this case, the fault starts with the sinusoidal steady-state current, with the fastest increase at its current zero that is, at the moment of the fault occurrence (thick line in Fig. 6.33). From now on, we assume that such a current heats up the fuse element.

![Fig. 6.33. Time functions of short-circuit currents](image)
If the fuse interrupts an MV fault, an equivalent circuit without serial damping provides a good approximation (Fig. 6.34). According to this:

\[ v = L \cdot \frac{di}{dt} + v_f \]  

(6-3)

where \( v \) is the voltage measured across the terminals of the fuse. The voltage of the fuse element after melting is \( v_f \approx v_{arc} \), thus

\[ v_{arc} = v_f = u \cdot L \cdot \frac{di}{dt}. \]  

(6-4)

The slope \( \frac{di}{dt} \) is negative during the decrease of the current; therefore the voltage of the inductance is added to the supply voltage. Since the current must decrease over the time of arcing, the condition of \( v_f \) must be satisfied. It can be observed in Fig. 6.34 that the fuse element melts before the prospective current \( i \) reaches its peak. This indicates a current limiting behavior. The voltage of the fuse has been growing before melting, because the temperature rise raised the resistance of the fuse element. A significant increase of this voltage – above the supply voltage – happens only after arc occurrence. The highest voltage can be expected at two moments: after melting of the fuse element \( \hat{V}_1 \) or during the TRV after the final extinction of the arc \( \hat{V}_2 \). With MV systems having small rated currents, \( \hat{V}_2 \) is usually higher than \( \hat{V}_1 \). The standards allow the following value as an upper limit for the voltage peak in an MV system:

\[ \hat{V} = 2.2 \cdot \hat{V}_n \]  

(6-5)

where \( \hat{V}_n \) is the peak of the rated line-to-line voltage. For instance, if \( V_{	ext{r}} \approx 40.5 \text{ kV} \), then \( \hat{V} \approx 126 \text{ kV} \).
Fig. 6.35. Fuse elements of MV fuses

If the whole fuse element melted and evaporated at once along its length during a fault operation, then the overvoltage would become extremely high. Therefore, it is important that the disruption of the fuse element should happen only progressively with more smaller, consecutive voltage peaks exceeding the momentary value of $v$ only a little. Regarding this condition, favorable operation can be achieved by fuse elements with densely varying cross sections. Some examples of such elements with circular and flat cross sections are shown in Fig. 6.35. The thinner parts correspond to the rated current of the fuse, although the thicker parts make possible that the cross section of the thin sections can be smaller than it would be with constant sized elements. The elements melt at the thinner segments first, resulting in increased current limiting capability. If the fuse link contains several of such identical elements connected in parallel, then the amount of metal vapor and the degree of ionization becomes less in the individual arcs of each element.

Fig. 6.36. Melting of fuse element and arc formation

The rated voltage determines the length of the fuse element. For instance, the minimum length with constant cross section (according to Mihailov):

$$l_{\text{min}} = 160 + 70 \cdot V_r^{0.75}$$

(6-6)

The fuse element is embedded in quartz sand. After the element melts, a portion of its material vaporizes and a remainder flows away in liquid form. In the channel formed by this process, an arc starts to burn. Smaller the element cross section, less is the amount of metal vapor and the inner diameter of the channel, resulting in better arc cooling. Arc is initiated at the thinner sections of the element first. The element falls apart forming droplets and gaps. The arcs in the gaps are connected in series, multiplying the anode and cathode drops. Finally, the entire element vaporizes and the arc burns along the whole length of the remaining channel (Fig. 6.36). The high pressure metal vapor is deposited on the surface of the quartz grains, and the grains fuse and stick together in the vicinity of the arc. The mixture of these materials is known as fulgurite. The channel formed this way effectively contributes to the arc quenching process. It compresses the arc, raising its pressure, and forms a parallel conducting path. The resistance of this path progressively decreases toward the current zero, as the channel cools down. Figure 6.37 shows these channels remained after the arc extinction in an MV fuse link.
containing five parallel elements. The thicker channels were formed at the thinner parts of the elements, as the arc burned there for a longer time.

Fig. 6.37. Channels remaining after an MV fuse has blown

During the interruption process, the fuse is exposed to the thermal stress of the arc energy and to the mechanical stress of the arc pressure.

Regarding the **thermal stress**, the arc energy \( W_{arc} \) is a relevant quantity. With *given fault current (consisting a DC component as well)*, \( W_{arc} \) reaches its maximum if the fault occurs during the increasing part of the voltage; to be more precise, if the current is initiated about 1 rad after voltage zero, and arcing starts in the hatched range of Fig. 6.38. Current limiting capability depends also on the magnitude of the prospective current \( I_r \), and at a critical \( I_r \), the arc energy will reach its possible maximum. Figure 6.39 illustrates the variation of \( W_{arc} \) as function of \( I_r/I_n \). The critical short-circuit current in this case is \( I_{n_c}=60I_n \), although generally, it can be in the range of \( I_{n_c}=(30…100)I_n \).

![Fig. 6.38. Determining the arc energy regarding thermal stress](image)

We can expect the highest **mechanical stress** with the current corresponding to the breaking capacity \( I_{m} \), as the let-through current, the speed of vaporization, and the pressure reach their maximum in this case. The rms value of the breaking capacity is given by the regulations. E.g. for MV fuses with a rated voltage of \( V_r=12 \text{ kV} \) and a rated current of \( I_r=10…100 \text{ A} \), it is \( I_{m}=50 \text{ kA} \).

![Fig. 6.39. Variation of arc energy](image)
Sizing the fuse concerning short-circuit currents practically means the selection of the appropriate fuse regarding the current limiting capability. In fact, we size the fuse concerning the current at the moment of melting, instead of the let-through current. It is clear from Fig. 6.40 that the let-through current can slightly (by 7…10 %) exceed the melting current, because $v_{arc} > v$ during the melting process of the thin fuse element sections. If we apply the relations obtained for the fast (short-circuit) temperature rise (see section 3.2) by integrating up to the moment of melting $t_{melt}$ (pre-arcing time) that is, from the initial temperature $\vartheta_i$ to the melting temperature $\vartheta_{melt}$ or from the initial temperature rise $\tau_i = \vartheta_i - \vartheta_o$ the temperature rise at the time instant of melting $\tau_{melt} = \vartheta_{melt} - \vartheta_o$, then:

$$
\int_0^t I^2 dt = A^2 \cdot \frac{\varrho}{\varrho_o} \ln \frac{1 + \alpha(\vartheta_{melt} - \vartheta_o)}{1 + \alpha(\vartheta_i - \vartheta_o)}
$$

(6.7)

where the fusing Joule-integral (denoted by $(I^2 t)_{melt}$) on the left side of the equation is proportional to the cross sectional area $A$ of the fuse element. In case of parallel elements, $A$ is the sum of the elements’ cross sectional areas. Equation (6.7) yields the necessary element cross section ensuring a specific melting time, namely current limitation. The manufacturers usually provide the Joule-integral values as functions of the prospective current and the rated current in form of diagrams. Figure 6.41 shows the cut-off (let-through) current characteristics of MV fuses with rated currents of $I_r = 6.3…100$ A.

3.1.2. Overload operation

In case of overloads, because of the long duration of the heating, we can neglect the switching transients, and we can assume that the heat power is proportional to the square of the rms current ($I$). The relations valid for slow processes and discussed in section 3.1 can be applied to calculate the time of melting. Compared to this duration, the arcing time is very short; therefore, the melting and clearing times can be taken to be equal. The diagrams in Fig. 6.42 help to understand the operation of fuses in the order of overload currents. Each heating curves correspond to different currents. For better understanding, at the moment of $t=0$, the temperature rise is zero that is, we assume that no current has been flowing previously, or the fuse element has cooled back to the ambient temperature.
The steady-state temperature rise belonging to the lowest fusing current $I_l$ equals exactly to the temperature rise of melting ($\tau_{\text{melt}}$). This indicates that with $I_l$, the fuse element melts after infinite time. If the current is more than this current limit ($I_l < I$), the element will fuse, and the time of operation is determined by $\tau_{\text{melt}}$. If it is less ($I < I_l$), the element will not fuse. Higher the current, shorter the operating time, as it is clear from the diagrams of Fig. 6.42: if $I_2 > I_1$, then $t_{\tau_{2}} < t_{\tau_{1}}$. The theoretical time-current characteristic in Fig. 6.43 reflect these observations. It is clear that the rated current $I_r$ of the fuse is less than the lowest fusing current ($I_r < I_l$). Although, it would be advantageous for the system designers if $I_r$ and $I_l$ were the same, but unfortunately this cannot be satisfied for two reasons:

1. The fuse element would operate continuously close to its melting point. The extended oxidation and diffusion would lead to increased fatigue, making fuse lifetime shorter.

2. The growth of resistivity close to the melting point would result in a 4...5 times increase in fuse element resistance, and consequently in its loss.

Because of the inaccuracies during manufacturing and the different application conditions, in practice, it is possible to keep $I_l$ only in a specific range determined by a tolerance. In a favorable case, this range is $I_r=(1.1...1.5) \cdot I_l$, whereas in an unfavorable one it is $I_r=(1.3...2.0) \cdot I_l$. Manufacturers always provide the rated current. As a consequence, in the range of $I_r=(1.3...2.0) \cdot I_l$, or $I_r=(1.1...1.5) \cdot I_l$, fuses cannot ensure protection against overloads.

This is why fuses are not appropriate for precise overload protection, and they are not used for this task in practical applications. For example, if we wanted to protect our system with a fuse having a rated current $I_r=16$ A against a long lasting overcurrent of 32 A, which is double of $I_r$, then – considering that $I_r=2 \cdot I_r$ – this current would not melt the element. Instead, as losses quadruple with double current, the wires would overheat, their insulation might melt, leading to the risk of fire.

The manufacturer gives only the rated current, although we have to select a fuse according to the lowest fusing current. The following approximating equation can be written for an $l$ long section of the fuse element, having a cross sectional area $A$:

$$\tau_{\text{melt}} = \frac{l \cdot \rho_{\text{melt}}}{\sigma_{\text{melt}}} = \frac{l \cdot \rho_{\text{melt}}'}{\sigma_{\text{melt}}' \cdot l' \cdot \rho_{\text{melt}}'},$$

(6-8)
where $R_{melt}$, $\alpha_{melt}$ and $\rho_{melt}$ are the resistance, film coefficient and resistivity of the fuse element at its melting temperature, respectively. Furthermore, $S$ is the surface area of heat transfer, and $k$ is the circumference of this surface in its cross section. By expressing $I_l$ from the previous relation:

$$I_l = \sqrt{\frac{C_{cor}}{\rho_{melt}}} \cdot \sqrt{A \cdot k},$$

(6.9)

that is, the lowest fusing current is proportional to square root of the product $A \cdot k$. We have seen that for short-circuit protection, the cross sectional area $A$ had to be determined. To satisfy both conditions together, a circular cross section is usually not appropriate. To be able to adjust both the circumference and the area, we need flat fuse elements and/or elements connected parallel.

Fig. 6.44 shows the time-current characteristics of MV fuses having different rated currents. The curves indicate average operating times, and the times below 10...50 ms are virtual melting times determined from the rate of the operating Joule-integral and the rms prospective current square.

![Time-current characteristics of MV fuses](image)

**3.1.3. Structure**

Figure 6.45. shows an MV fuse link inserted in a traditional fuse base. The fuse bases and fuse links made recently for indoor switchgears can differ from that presented in the figure. The numbers indicate the following structural items: 2. fuse link, 3. cylindrical contact, 4. spring contacts, 5. porcelain tube, 6. fuse elements, 7. ceramic fuse element holder, 8. granular quartz sand filler, 9 terminals, 10. cap, 11. striker of fuse indicator, 12. earthing bolt. It is clear that the parallel fuse elements of the fuse link are wound on a ceramic cylinder situated inside a porcelain tube. This tube is filled with granular quartz of grain sizes in the region of 0.15...0.4 mm. Low grain size can improve cooling, but can impede the diffusion of metal vapor. The striker, when the fuse operates, releases the energy of a pre-stressed spring required to cause operation of the fuse blow indicator or other apparatus (e.g. a switch) that provides interlocking. The standards fix the sizes of MV fuses.

![Structure of an MV fuse](image)
3.2. Low voltage fuses

First, we treat the construction and main properties of LV fuses. Then, we discuss some of their unique operating features when disconnecting short-circuit and overload currents, which features are independent from their structure, but different from that of the MV fuses. The structure of the fuse element and its environment highly affects the operation of LV fuses; therefore, we have to present the basic principles of these items and some details of their construction. We show the characteristic curves of fuses, but we do not discuss the sizing of the fuse element, as the method is the same as for MV fuses. Finally, we deal with the selection of LV fuses.

3.2.1. Structure and properties

We present three LV fuse types having different constructions: D-type (end contact or screw type), blade type (NH type), and cylindrical-cap-contact fuses. A fuse base connected into the electrical system and capable of holding a fuse link, and a fuse link, which includes the fuse element(s) are part of all the tree types.

The material of the elements in the fuse link can be copper, silver plated copper, or silver. A solder of low melting point metal might be fixed on the surface of the element. The fuse element is usually surrounded by dried granular quartz sand of high chemical purity and grain sizes more than 0.3 mm, which is compacted by vibration.

The D and NH types of fuses are equipped with blow-out indicators, which provide a visual sign if the element inside the fuse link has melted. Figure 6.46 illustrates the operation principle of such a blow-out indicator. After melting of the main element, the current transfers to a fine, parallel connected auxiliary element made from high resistivity material. This melts quickly and releases a plunger, which is driven out by a spring. The color of this plunger corresponds to the rated current of the fuse.

![Fig. 6.46. Blow-out indicator of an LV fuse](image)

All the three fuse types are used in both single-phase and three-phase circuits. In case of a three-phase short-circuit, a recovery voltage of \( V_r = 1.4 \cdot V_{pn} \) can appear across the terminals of the fuse, which operated first. Here, \( V_{pn} \) is the phase-to-neutral voltage of the system. After a double earth fault, even the line-to-line voltage can be measured on the terminals. As a consequence, the rated voltage of fuses used in LV 400/230 V networks is \( V_r = 500 \, V \).

3.2.1.1. a.) D-type (end contact or screw type) fuses

The mark D of these fuses comes form their old name „Diazed“. „Dia” indicates that accidental replacement of the fuse links with another one having inappropriate rated current is prohibited by the adjusted diameter of the porcelain gauge ring. The „z” („zweiteilig”) implies that the fuse base has two pieces, and „ed” is an abbreviation for Edison screw base (E16, E27 or E33).

![Fig. 6.47. D-type fuse link](image)

In the fuse link of Fig. 6.47, a heat and pressure resistant ceramic (porcelain or steatite) case (7) encompasses the main element (3) and the auxiliary element (6) of the fuse indicator. The elements are embedded in quartz sand filler (4). The end caps of the top (1) and bottom (5) contacts are compressed on the ceramic body, together
with both ends of the main element and the bottom end of the auxiliary element. The other end of the auxiliary element is attached to the plunger (2) of the blow-out indicator. The main fuse element has a constant circular, or varying flat cross section along its length. The diameter of the bottom contact corresponds to the rated current of the fuse link: greater the current, greater the diameter.

Fig. 6.48. D-type fuse

The ceramic fuse base consists of two pieces, the screw cap (8) and the fuse holder (11). The fuse link (9) has to be inserted into the screw cap and both are screwed into the fuse holder (see Fig. 6.48). The fuse link is fixed by a spring in the cap, thus unscrewing the cap removes the fuse link as well. This is important regarding shock protection. The plunger on the top electrode is visible through a glass window on the screw cap. This lets us check if the fuse has blown, or we can easily identify the rated current by the color of the plunger. A fuse link can be inserted into the holder that is, the contacts of the fuse base and the fuse link can be connected only, if the bottom electrode of the fuse link fits into the inner hole of the gauge ring (10). The gauge ring is part of the fuse holder, and its various internal diameters and colored ends indicate the maximum ratings of fuse links, which will fit into. The appropriate ring ensures that a fuse link of too great a rating for the circuit being protected may not be installed. It is not possible to touch any live parts, if the D-type fuse is appropriately assembled. However, the contacts can be touched, if the cap and the fuse link are removed. In this case, the danger of electric shock can be reduced if the fuse base is installed with the bottom contact connected to the live.

The rated voltage of the D-type fuse links is \( V_r = 500 \) V, their rated current is between \( I_r = 2...63 \) A, and their current breaking capacity is usually \( I_{(m)} = 50 \) kA. The fuse links and fuse bases are manufactured in three different sizes. The smallest fuse holder denoted by E16 can be used for fuse links with rated currents \( I_r = 2...25 \) A, the medium sized E27 also for \( I_r = 2...25 \) A, and fuse links of \( I_r = 35...63 \) A can be inserted into the largest one E33.

3.2.1.2. b.) NH type (Blade type) fuses

High power, blade type fuses can interrupt greater short-circuit currents, and their rated current can also be more than of D-type fuses. The abbreviation NH refers to „Niederspannungs Hochleitungs” meaning low-voltage high-breaking-capacity. The structure of an NH fuse link can be observed in Fig. 6.49. The heat and pressure resistant (usually ceramic) case (8) encompasses the fuse element(s) (3) and the auxiliary element (4) of the fuse indicator (1). There can be more than one flat elements connected parallel with varying cross sectional area. These, together with the fine auxiliary element are surrounded by quartz sand filler (2), and their ends are point welded to the contact blades (7). The two ends of the enclosure are terminated by metal plates (6) having high mechanical strength. These plates are separated from the body by thermal insulating spacers (5), and are attached to it by screws. Sometimes, the fuse indicator is placed in the center of the enclosure.

Fig. 6.49. Blade type LV fuse link
Fig. 6.50. Blade type fuse

Fig. 6.50 shows an NH fuse link (9) placed into its fuse base. The blades are inserted into spring contacts (10), which keep the fuse link in the base. It is clear from the figure that the (usually vertical) connection of the conductors forms a loop resulting in an electrodynam force that tries to open the circuit. Appropriate spring pressure and frictional force or possibly the use of a clamp can counteract the opening force. As a consequence, inserting the fuse link into the fuse holder or removing it from there needs a major effort from the operator even when no voltage is applied to the terminals. A detachable plastic handle makes the replacement of the fuse link easier, and it can be used even during live maintenance.

Blade type fuse links are generally available for applications with rated currents in the range of $I_r = 2 \ldots 1250$ A, and they provide a current breaking capacity of $I_{(m)} = 100$ kA. NH fuse links and fuse bases are manufactured usually in six different sizes, denoted by 00, 0, 1, 2, 3, and 4 with increasing size respectively. The rated currents of fuse links fitting into these fuse bases are 00/2...160 A, 0/6...160 A, 1/6...250 A, 2/25...400 A, 3/63...630 A and 4/400...1600 A.

3.2.1.3. c.) Cylindrical cap contact fuses

Cylindrical cap contact fuses are generally used for the fault protection of low power equipment or measuring instruments in single-phase systems having less than 250 V rated voltage. The prospective short-circuit current in the circuits to be protected is less than 100 A. They are made with rated currents in the range of $I_r = 5 \text{ mA} \ldots 15 \text{ A}$.

Fig. 6.51. Cylindrical cap contact fuse link

Figure 6.51 shows the cross sectional view of a cylindrical cap contact fuse link. The fuse element (3) is a thin wire with constant circular cross section along its whole length. It is soldered to the metal caps (2) pressed on the ends of a glass tube (1), and is surrounded by quartz sand (4) in the fuse link of the figure. With small rated currents, no quartz sand is used, the filler is air.

The fuse link can be inserted by its caps into the fuse holder, which is built into the device to be protected. Another, probably better solution is the plastic enclosed fuse holder fixed to the housing of the protected unit (see Fig. 6.52). It makes possible the easy replacement of the fuse link, even if its terminals are energized. The fuse link (7) can be inserted into the fuse base (8) by releasing or fixing the end cap (5), which includes a spring (6).

Fig. 6.52. Cylindrical cap contact fuse

3.2.2. Operation during short-circuit
We have discussed the short-circuit operation of MV fuses in section 6.3.1.1. Theoretically, the fault behavior of LV fuses is the same, although there are some dissimilarities. One of them is that the serial resistance plays an important role in LV circuits. We examine the short-circuit operation in a system with a power factor of cos ϕ=0.5, and with the possible steepest initial slope of the current (Fig. 6.53). The following equation is valid for this circuit:

\[ v_{arc} = v_f = v \cdot i \cdot R \cdot L \cdot \frac{di}{dt} \]

(6-10)

It is clear form the previous equation that the current during the arcing period can decrease only, if the condition \( v_f > v_i \cdot R \) is fulfilled.

![Fig. 6.53. LV fuse; time functions during short-circuit](image)

The diagrams in Fig. 6.53 indicate that after the element melts at \( I_{melt} \), the current slightly increases (by 7...10 %) until it reaches the let-through current \( I_{lt} \). This happens before the prospective current \( (i_F) \) arrives at its peak (see also Fig. 6.40). The arc voltage starts to increase significantly after the melting of the element, and finally exceeds the voltage \( v_i \cdot R \). As a result, the fault current decreases, and reaching zero, it eventually ceases to flow if the arc does not reignite. The fault clearing or operating time \( I_o \) of the fuse consists of two parts: the pre-arching time \( t_{melt} \), and the arcing time \( t_{arc} \). Like previously with MV fuses, the highest voltage across the fuse can occur in two cases: during the arcing period \( V_1 \), or after the final extinction of the arc \( V_2 \). The voltage limit allowed by the standards for fuses with \( V_r=500 \) V is \( \hat{V}_f = 2500 \) V. Furthermore, Fig. 6.53 indicates that, because of the resistance \( R \) of the LV circuit, the arc voltage, and consequently the value of \( \hat{V}_1 \) might be slightly smaller than in solely inductive MV systems. However, the phase shift of the fault current is less by \( \pi/2 \), resulting in higher TRV, as the oscillating component of the recovery voltage is superimposed on a higher steady-state component after the current zero. This raises the value of \( \hat{V}_2 \) significantly.

The influence of the reduced phase shift is largely disadvantageous for \( \hat{V}_2 \), if the arc in the fuse becomes unstable before the current zero that is, if current chopping occurs. Although the chopped current is just some amps, the magnitude of the overvoltage can be significant, especially in the critical range of the short circuit current (see Fig. 6.39). In this case, the inductance, and therefore the stored magnetic energy of the circuit (which is converted into capacitive energy) is high. With very high fault currents, the significance of current chopping is less, as the phase shift is less than \( \pi/2 \), and the inductance of the circuit is small.
We have seen that fuse elements with constant cross section are also used in D-type and in cylindrical cap contact fuses. These elements melt and vaporize at once along their whole length, instantly inserting a high arc resistance and consequently high arc voltage into the circuit. This results in a sudden decrease of the current, and \( I = I_{\text{melt}} \). The breaking capacity of the fuse can be raised that is, the pre-arcing time \( t_{\text{melt}} \) can be reduced by greater arc voltage. The quartz sand surrounding the element contributes to this voltage as well, and can make the arc gradient \( E_{\text{arc}} \approx 280 \text{ V/cm} \) instead of the gradient \( 14 \text{ V/cm} \) in air. We have learnt the melting, vaporizing and arcing processes of such an element in Fig. 6.36. Further increase of the arc gradient can be achieved by a longer arc, namely by a longer element. Although the overvoltage appearing after fusing limits our possibilities, which are anyway confined to the short size of D-type and cap contact fuses. The simultaneous melt and vaporization of the entire element can result in a TRV and overvoltage higher than necessary, probably even more than allowed. An auxiliary element with high melting temperature parallel with the main element can make the TRV less. The resistance of the wolfram auxiliary element grows rapidly, it can reach 16 times of its value at room temperature close to the melting point. With appropriate sizing, this effect can make the TRV aperiodic that is, it can reduce \( \dot{V}_{Z} \) to the momentary supply voltage, after melting of the main element. Finally, the auxiliary element melts as well. Although this method cannot make the arc voltage smaller, only the TRV, this can be advantageous in some cases.

Constant fuse element cross section practically limits the achievable current breaking capacity and the current limiting capability. Generally, this is not enough for practical cases when increased breaking capacity and current limiting capability are expected from the fuse. Dense perforation of the fuse element can confine the melting and the arc to multiple points, which results in appropriate breaking and current limiting capabilities accompanied by acceptable overvoltage values. Figure 6.54 shows some shapes used with flat, ribbon elements in blade type, high power LV fuses. Sometimes, similar fuse elements appear in D-type fuses as well. The fuse, and consequently its fuse elements have to be able to conduct the rated current continuously for an unlimited time. This holds true for the thin element regions as well, the cross sectional area of which is less than that would be necessary with a constant cross section. The rate of cross sections between the thin and thick regions is: 1/8...1/4.

The element does not melt and vaporize simultaneously along its entire length, if it has a varying cross section. First, the thin regions of the element – or groups of these regions – melt one after the other, connecting several arcs in series. The resulting voltage of the small arcs surpasses the voltage \( v \cdot i \cdot R \) only as much as it is necessary for the appropriate reduction of the current, therefore extremely high overvoltage does not occur. After melting of the first thin sections, the current still increases slightly, as we have seen in figures 6.40 and 6.53. We note that the melting, vaporization and arcing processes of the thin sections are similar to the one illustrated in Fig. 6.36. The only difference is that the arc grows longer than the length of the thin segment \( d_{\text{in}} \), as the arc make some of the thicker parts vaporize.

The manufacturers provide the values of the let-through (cut-off) current \( I_{\text{lt}} \), and the values of the pre-arcing and operating Joule integrals \( (I^2 t)_{\text{melt}} \) and \( (I^2 t)_{\text{arc}} \), respectively) in diagrams as functions of the prospective current \( I_{F} \) and the rated current \( I_{r} \) of the fuse. They determine these data by measurements. Besides, the values of \( (I^2 t)_{\text{melt}} \) and \( I_{\text{lt}} \) can be calculated approximately according to the relation (7.10). The cut-off current characteristics of D-type and NH-type LV fuses are similar to that of MV fuses (see Fig. 6.41). The values of \( (I^2 t)_{\text{melt}} \) and \( (I^2 t)_{\text{arc}} \), are plotted in figures 6.55 and 6.55 respectively, for fast, D-type fuse links.
3.2.3. Operation during overloads

In case of overload, if there is only one element in the fuse link, the element melts at one point (or at some points). An arc occurs here, the length of which continuously increases during several half-cycles until the supply voltage is not able to reignite it. If there are more parallel elements, the melting process is more complicated. For instance, with two parallel elements, only one of them melts first along a short section without any arc. Thereupon, the doubled current density melts the other one rapidly, the arc lengthens and extinguishes. After (or during) this process, due to the growing voltage, a breakdown occurs in the short gap created previously in the first element, reigniting the arc. After reaching a specific length, the arc disappears again. During the long pre-arcing and arcing times the temperature of the fuse link rises significantly. Generally, the highest temperature rise of the fuse link can be expected in the overload range of $I = (1.4...2.0) \cdot I_n$.

Owing to their minor size, the fuse elements have a much smaller thermal inertia than of the conductor or equipment to be protected. Consequently, with varying operating currents, the protected devices could not be used appropriately or at all. For instance, the same happens, when the in-rush current of an electric motor melts the elements in a fast operating fuse. Therefore, the operation of fuses has to be delayed in the range of short overload currents. Slow and combined, slow-fast fuses are applied for similar cases. However, the short-circuit protection of semiconductor devices needs an opposite measure. For the protection of such equipment, ultra fast fuse links are produced.

Figure 6.57 shows time-current characteristics of slow (S), fast (F), and ultra fast (UF) fuses, whereas a combined characteristic curve (S-F) is plotted in Fig. 6.58. According to the standards, currently, the types of LV fuse links are designated by two letters. The second letter describes the utilization category, as it is listed in table 6.1, and the first letter describes the breaking range the manufacturer provides as follows:
1. Partial range: The characteristic curve is defined for all currents between the lowest current indicated and its rated breaking capacity.

1. Full range: The range is given for all currents, which cause the melting of the fuse element up to its rated breaking capacity.

Table 6.1. Utilization categories of LV fuse links

<table>
<thead>
<tr>
<th>Type</th>
<th>Utilization category</th>
<th>Breaking range</th>
</tr>
</thead>
<tbody>
<tr>
<td>gG</td>
<td>General application, mainly for conductor protection</td>
<td>Full range</td>
</tr>
<tr>
<td>gM</td>
<td>Motor circuit protection</td>
<td>Full range</td>
</tr>
<tr>
<td>gN</td>
<td>North American general application for conductor protection</td>
<td>Full range</td>
</tr>
<tr>
<td>gD</td>
<td>North American general application time delay</td>
<td>Full range</td>
</tr>
<tr>
<td>gR, gS</td>
<td>Semiconductor protection</td>
<td>Full range</td>
</tr>
<tr>
<td>gU</td>
<td>Wedge tightening fuse for utilities</td>
<td>Full range</td>
</tr>
<tr>
<td>gL, gF, gI, gII</td>
<td>Former type of fuse for conductor protection (replaced by gG type)</td>
<td>Full range</td>
</tr>
<tr>
<td>aM</td>
<td>Short-circuit protection of motor circuits</td>
<td>Partial range (back-up)</td>
</tr>
<tr>
<td>aR</td>
<td>Semiconductor protection</td>
<td>Partial range (back-up)</td>
</tr>
</tbody>
</table>
The heat flow from the thin to the thick regions in the flat fuse elements of Fig. 6.54 prolongs the heating process. Therefore, flat elements with varying cross section can also delay the operation. This appears like an increase in the thermal time constant of the fuse. This delay can be raised if a low melting point (e.g. 300 °C) metal globule (in practice Sn-Pb alloy) is soldered to one of the wider sections of the element, which has a much higher melting temperature than of the solder metal (Fig. 6.59). The heat generated by an overload current flows into the solder, the temperature of which grows only slowly (with a delay). After some time, the solder metal starts to diffuse into the element material, which has not reached its melting point. The diffused solder and the element material together form a high resistance alloy having a lower melting point than the element. Due to the increased heat generated in this part, finally the fuse element melts faster than it would without a solder. Consequently, the lowest fusing current of an element with metal solder is smaller than that without solder. It follows that the element of delayed fuse links has greater cross sectional area than that of fast fuse links with the same rated current. The rated current, the characteristic curve of delayed fuses or the slow region of combined characteristics can be adjusted and determined by the composition of the solder metal (Fig. 6.58).

![Fig. 6.59. Solder metal on a flat fuse element](image)

We have to note here that the fuse element degrades due to the current flowing through it. Currents, which are greater than the rated value, but do not cause fusing, accelerate the aging process. An old fuse link might operate in a shorter time than a new one, even under its rated current. This can result in unwanted and unnecessary disconnection of loads and can disturb the selective operation of the electrical system.

Blade type fuse links with a slow-fast characteristic curve and with rated current of $I_r=40$ A were exposed to a forced ageing process consisting of 500 repetitions of 45 minutes load at $1.2 \cdot I_r$ and 15 minutes no-load cycles. It was observed that many fuse links operated before the ageing has been finished, and at the end, the remaining, seemingly healthy fuse links interrupted a current of $2.5 \cdot I_r$, almost two times faster than their new counterparts. The reason of this is that the metal solder partly or completely diffuses into the copper element. The photo in Fig. 6.60 shows a fuse element, with a solder diffused through its whole cross section. A further magnified picture of a solder partially penetrated into the element material can be seen in Fig. 6.61. The hardness tester caused the deepest indentation in the solder, the smallest in the layer where the two metals mixed. This rigid compound is responsible for the disadvantageous operation of the fuse. The mechanical strain caused by the heat of the changed load current breaks the fuse element at this point, and the resulting arc starts to melt the element.

![Fig. 6.60. Solder metal completely diffused through the fuse element](image)
The ultra fast D and blade type fuses are used mostly for short-circuit protection of high power semiconductors, but they are regularly applied in series with circuit breakers as well. They include special shaped silver fuse elements (e.g. see Fig. 6.62) with narrow constrictions. Their operating time during faults is very short. Occasionally, the constrictions are surrounded by glass-silicone plates. These improve mechanical strength and contribute to arc quenching. The selection of these fuse links for short-circuit protection of semiconductors is based on the Joule-integral.

The average time-current characteristics of different, delayed, blade type LV fuses are plotted in Fig. 6.63. The shortest (less than 10...50 ms) operating times indicated in the diagrams are virtual operating times. The characteristic curves start with small operating times, when current limitation does not occur. Operating currents around $50 \cdot I_r$ belong to these times, indicating an approximate upper limit of the overload range.

Fuse links having different characteristic curves differ also in their current limiting capabilities. Slow fuse links limit the short-circuit current less, whereas ultra fast fuse links limit it in a much higher degree than fast devices with same rated current, as it can be observed in the cut-off (let-through) current diagrams in Fig. 6.64. The thicker element explains the decreased limiting capability of slow fuse links, whereas the smaller constrictions in the elements are responsible for the increased limiting capability of ultra fast fuse links.
3.2.4. Selection

When selecting fuses, the general rules of switching device selection have to be considered as well. Among these rules, we focus on some passive and active electrical properties of fuses and discuss their selection considering coordinated operation, and the verification of coordination.

First, we deal with the following **passive and active electrical properties**, and their verification.

1. The overload currents belonging to the normal operation of the electrical equipment to be protected must not trigger a fuse operation. To satisfy this condition with slow or slow-fast fuses, we have to take the operating conditions – that is, the utilization category (see section 6.5) – and the rated current $I_{ru}$ of the protected equipment into account. The relation $I_{ru}=(1.0 \ldots 3.0)\cdot I_{req}$ determines the rated current of the fuse $I_r$. The term in the brackets, for instance, is 1.0 for the protection of cables or conductors; 1.0 ... 1.2 for slip ring asynchronous motors; 1.2 ... 1.5 for soft starting of squirrel-cage motors; 1.5 ... 3 for hard starting of squirrel-cage motors. The higher values are selected, if there is a separate overload protection.

2. We have seen that the lowest fusing current of a fuse is $I_{fr}=1.2 \ldots 4.5\cdot I_{req}$, that is, the fuse does not provide any protection in the current range of $I_{fr}$. Therefore the installation of a separate overload protection is unavoidable, which can grant the protection in the range of $(1.05 \ldots 3.0)\cdot I_{fr}$. The situation is even worse with the fuse at the supply, farther upstream from the point of the fault if the protective system is coordinated. In this case, the rated current of this fuse has to be significantly higher than that of the circuit where the fault occurs.

3. The current breaking capacity of the fuse must not be less than the prospective short-circuit current at the point of installation.

4. The let-through current $I_{lt}$ of the fuse has to be less than the peak withstand current of the device $I_{we}$.

5. The operating Joule-integral of the fuse has to be less than the Joule-integral allowed for the device to be protected.

We discuss **selective operation or coordination** regarding fuses connected in series upstream and downstream in a system, a fuse upstream and an MCB downstream, and a fuse connected in series with a general purpose CB or a motor protective switch. Selective operation means that in case of a fault, only the protective device closer to the point of fault operates, or that the fuse protects the switching device connected in series downstream to it.

1. Selective operation of fuses connected in series can be ensured in the overload range only, if the average time-current characteristic curves do not overlap within a tolerance. We have seen that the upper limit of the overload range can reach up to $50\cdot I_r$. An appropriate selectivity can be accomplished with fuses complying with the requirements of the standards regarding the time-current characteristics (see Fig. 6.63), if the ratio of the rated currents of the fuses is more than $I_{fr}/I_{we}=1.6$.

2. In case of a short-circuit occurring downstream in a load circuit, namely when current limitation is expected, selective operation between the upstream and downstream fuses can be achieved only, if the operating Joule-integral of the fuse downstream $(I^2\cdot t)_{ru}$ is less than that of the fuse upstream $(I^2\cdot t)_{ru}$. In Fig. 6.65, a downstream fuse with rated current $I_{ru}$ protects the load circuit, where a fault occurs. An upstream fuse with rated current $I_{ru}>I_{ru}$ is installed in the supply connection. By plotting the Joule-integrals as functions of the rms prospective current $I_{fr}$, it is clear that the condition of selective operation can be fulfilled only up to the current $I_{fr}$. If the prospective fault current exceeds this value, then both fuses will operate. By replacing the upstream fuse to another (probably delayed) one with a rated current $I_{ru}$, and with a pre-arcing Joule-integral $(I^2\cdot t)_{pre}>(I^2\cdot t)_{ru}$, the limit of selective operation can be extended to currents higher than $I_{fr}$, possibly even up to the current breaking capacity of the downstream fuse. The dashed line in Fig. 6.65 indicates this possibility.
1. In the system of Fig. 6.66, a current limiting MCB or CB with rated current of $I_{r1}$ and operating Joule-integral of $(I^2 t)_{\text{o1}}$ protects the downstream load circuit. A fuse with a rated current of $I_{r2} > I_{r1}$, a pre-arcing Joule-integral of $(I^2 t)_{\text{melt}}$, and an operating Joule-integral of $(I^2 t)_{\text{o2}}$ is installed in the supply connection. According to the diagrams in Fig. 6.66, it is clear that selective fault operation can be ensured only up to the prospective fault current of $I_{FA}$. If the current surpasses this limit, both switching devices will operate. Between the currents $I_{FA}$ and $I_{FB}$, the temperature rise of the protected device corresponds to $(I^2 t)_{\text{o1}}$. If the current exceeds $I_{FB}$, the temperature rise will be determined by $(I^2 t)_{\text{m2}}$. The current limit $I_{FA}$ can be increased by selecting a fuse with higher rated current, and probably with delayed operation.

4. Disconnectors

The high and medium voltage **disconnectors** or **isolators** are mechanical switching devices, which provide complete insulation distance called isolation distance between their open contacts. They have to satisfy safety and electrical requirements regarding their open contacts that is, as their **major task**, they have to provide safe and visible separation between parts of the electrical system. They have negligible current interrupting
capability and are only used in the off-load condition. They can be operated only if negligible current flows through them, or if the voltage across their contacts is insignificant. If their contacts are closed, they have to be able to conduct rated current for unlimited time and they have to withstand the thermal and dynamic effects of short-circuit currents. Their secondary task is to arrange the path of the current. An example is a double busbar system, where disconnectors provide the way for the power flow between the busbars. Disconnectors are often equipped with earthing switches or earthing knives.

The insulation between the open contacts of a disconnector has to be tested with different test voltages. These can be lightning impulse withstand voltage (1,2/50 μs), power frequency withstand voltage, and switching impulse withstand voltage (250/2500 μs). The magnitude of these test voltages depends on the rated voltage $V_r$. We note that the smallest breakdown voltage in air can be expected with a switching impulse.

The standard provides values for all the three test voltages that the disconnector has to withstand between its open contacts and between the contacts and earth. Up to $V_r=245$ kV, disconnectors have to be tested only with power frequency and lightning impulse test voltages.

![Fig. 6.68. Insulation levels](image)

Atmospheric overvoltages can be so high that insulation against them is not feasible to implement economically. Instead, different insulation levels are defined, and the electric strength of equipment is selected regarding the voltages which can appear in the system for which the equipment is intended. The overall aim of insulation coordination is to reduce the cost and disturbance caused by insulation failure to an economically and operatingly acceptable level by allowing flashovers only at intended points. In Fig. 6.68 the insulation levels low, medium and high are indicated. The low level belongs to the surge arresters, the medium to the operating voltage of rod gap arresters, and the high (safety) level to the open contacts of the disconnectors. The standard provides impulse withstand voltages for all levels.

If its contacts are open, the disconnector ensures the safe separation of equipment from the supply system, namely voltage cannot appear on the equipment. To guarantee this condition, in case of an overvoltage, sparkover or flashover must not occur between the open contacts of the disconnector, but it can occur between the any of the contacts and earth. The disconnector is coordinated in itself, if it satisfies this condition without any overvoltage protective device. This self-coordination was required by older regulations. However, a flashover to earth can be dangerous for the maintenance personnel, therefore standards today require only an overvoltage protective device in the system with an operating voltage less than the breakdown voltage of the open disconnector contacts.

The rated current flowing through the closed contacts of a disconnector generates Joule-heat. Most of this heat is produced in the knives, across the contact resistances, and at the terminal connections. All these have to be considered to calculate the steady-state temperature rise $\tau_{st}$ and we have to know the size of the surface where heat can be transmitted to the environment, and the value of the heat transfer coefficient $\alpha$ over this surface. The steady-state temperature rise must be less than a permitted limit (e.g. for bare copper, it is $\tau_{st}=35^\circ$C), namely $\tau_{st}\leq\tau_{per}$. Resultant constriction resistance is inversely proportional to the number of parallel contact pairs. A single pair is used up to 600 A, two pairs up to 1200 A, and three or four pairs above 1200 A. Parallel knives results also in increased current carrying capacity, as the surface transferring the heat grows.

The short-circuit current results in an increased force, which is proportional to the current square. This force varies with double of the power frequency and can cause a harmful vibration. The time average force $F$ might open the disconnector knives, like in the two cases of Fig. 6.69 (expanding current loop). In the construction of Fig. 6.70, a closing force occurs. It is important that the contacts must not weld. The constriction force between the contacts acts against the pressing force, which is inversely proportional to the contact resistance and the temperature rise.
The main structural elements of the disconnectors are as follows. Terminal connections (to busbars or wires), supporting insulators (porcelain, or in indoor units epoxy is also used), contacts, current conductors, frame (mount, bearings, shafts), earthing knife and its frame, drive and auxiliary contacts. Disconnectors can be indoor or outdoor, the insulation between the contacts can be air, sulphur-hexafluoride gas or vacuum. We discuss only medium and low voltage disconnectors shortly.

With medium voltage disconnectors, all the three poles are usually mounted on a common frame, and one drive operates the three poles together via a shaft. These are mostly indoor units. Figure 6.71 shows an air insulated MV disconnector with two parallel knives.

Disconnector as a stand-alone device is rare in new low voltage installations. Sometimes, they are used as stand-alone units to isolate busbar sections in complex metal enclosed switchgears, or to separate circuits with rated currents of several thousand amps. Regarding the requirements, the general conditions valid for low voltage switching devices are to be considered. For instance, concerning dielectric strength, tests with impulse voltage
of 8 kV peak are mandatory. Low voltage disconnectors are always indoor units, and their structure (Fig. 6.72) is identical to an indoor, air insulated, three-pole, medium voltage disconnector. The rated current of these – mostly manual operated – units is usually $I_{\text{r}}=400\ldots3000$ A. Low voltage disconnectors are not capable to break or make current, although they can interrupt small load currents. In this case, the making and breaking current, together with the time constant and the power factor, is provided by the manufacturer.

In high voltage systems, circuit breakers serve as load break switches as well. At medium voltage, vacuum chambers and rotary arc SF$_6$ units – appropriate for CB purposes as well – are used as contactors. Besides, many other medium voltage switches with different arc quenching mechanisms are also in operation in different device combinations. We discuss these combined units in section 6.6, together with the low voltage device combinations. In this section we treat low voltage load break switches only, and further on we refer to them simply as switches.

The main task of low voltage switches is to make and break the currents of consumer loads during normal, and overload conditions, the latter one also belonging to the normal operation of the system. The stress and life time (or durability) of the switches, and consequently their applicability depends not only on the rated currents and rated voltages of the loads, but also on other parameters, like the power factor and the electrical time constant of the circuits they operate. Furthermore, their operating conditions and operating principles, which determine the magnitude and shape of current and voltage transients during switch-on and switch-off operations, also influence their applicability. To take these parameters and conditions into account, the different AC and DC load types are classified into utilization categories (groups) shown in tables 6.2 and 6.3. The utilization categories AC-4, DC-3 and DC-5 include the dynamic breaking and stopping, or reversing the motor rapidly by reversing motor primary connections (plugging). By inching (jogging) is understood energizing a motor once or repeatedly for short periods to obtain small movements of the driven mechanism. The parameters of the circuits for testing the durability and switching capability of the switches are provided for all the categories. These are the switch-on and switch-off current and voltage, the power factor ($\cos \varphi$) or the electrical time constant ($T$). For instance, the durability testing of the contactors with rated current $I_{\text{r}}>17$ A in the utilization category of AC-3 has to be accomplished with a switch-on current of $I_{\text{w}}=6\cdot I_{\text{r}}$, and with a switch-off current of $I_{\text{off}}=I_{\text{r}}$. With the group of AC-4, the values of testing currents are $I_{\text{w}}=I_{\text{off}}=6\cdot I_{\text{r}}$. The power factor is $\cos \varphi=0.35$ in both AC cases. The value of the test voltage is $V$, in three of the previously mentioned groups, and it is $V_{\text{off}}=0.17\cdot V_{\text{w}}$, during current interruption in category AC-3, because in this case the difference of the supply voltage and the voltage of the spinning motor appears across the contacts of the switch. Utilization categories AC-20 and DC-20 indicate that the switch is used as a disconnector. The groups AC-21...23 and DC-21...23 are related to the switching of grouped consumer loads.

Table 6.2. Examples of utilization categories for low-voltage switchgear and controlgear

<table>
<thead>
<tr>
<th>Nature of current</th>
<th>Utilization category</th>
<th>Typical applications</th>
</tr>
</thead>
</table>

Figure 6.72. Low voltage disconnector

5. Load break switches

The medium and low voltage (mechanical or semiconductor) load break switches can make or break currents during normal, operating conditions. These include some specific overload conditions as well. Furthermore, they have to be able to conduct currents different from normal conditions (faults) until the protective measures are taken.
### Structure and operation of electrical switching devices

<table>
<thead>
<tr>
<th>Alternating current (AC)</th>
<th>AC-1</th>
<th>Non-inductive or slightly inductive loads, resistance furnaces.</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC-2</td>
<td>Slip-ring motors: starting, switching off.</td>
<td></td>
</tr>
<tr>
<td>AC-3</td>
<td>Squirrel-cage motors: starting, switching off motors during running.</td>
<td></td>
</tr>
<tr>
<td>AC-4</td>
<td>Squirrel-cage motors: starting, plugging, inching.</td>
<td></td>
</tr>
<tr>
<td>AC-5a</td>
<td>Switching of electric discharge lamp control.</td>
<td></td>
</tr>
<tr>
<td>AC-5b</td>
<td>Switching of incandescent lamps.</td>
<td></td>
</tr>
<tr>
<td>AC-6a</td>
<td>Switching of squirrel-cage motors: starting, plugging, inching.</td>
<td></td>
</tr>
<tr>
<td>AC-6b</td>
<td>Switching of squirrel-cage motors: starting, plugging, inching.</td>
<td></td>
</tr>
<tr>
<td>AC-7a</td>
<td>Switching of transformer control.</td>
<td></td>
</tr>
<tr>
<td>AC-7b</td>
<td>Switching of capacitor banks.</td>
<td></td>
</tr>
<tr>
<td>AC-8a</td>
<td>Switching of transformer control with manual resetting of overload releases.</td>
<td></td>
</tr>
<tr>
<td>AC-8b</td>
<td>Switching of transformer control with automatic resetting of overload releases.</td>
<td></td>
</tr>
<tr>
<td>AC-12</td>
<td>Control of resistive loads and solid-state loads with isolation by opto-coupler.</td>
<td></td>
</tr>
<tr>
<td>AC-13</td>
<td>Control of solid-state loads with transformer isolation.</td>
<td></td>
</tr>
<tr>
<td>AC-14</td>
<td>Control of AC electromagnetic loads.</td>
<td></td>
</tr>
<tr>
<td>AC-15</td>
<td>Control of AC electromagnetic loads.</td>
<td></td>
</tr>
<tr>
<td>AC-20</td>
<td>Connecting and disconnecting under no-load conditions.</td>
<td></td>
</tr>
<tr>
<td>AC-21</td>
<td>Switching of resistive loads, including moderate overloads.</td>
<td></td>
</tr>
<tr>
<td>AC-22</td>
<td>Switching of resistive and inductive loads, including moderate overloads.</td>
<td></td>
</tr>
<tr>
<td>AC-23</td>
<td>Switching of motor loads or other highly inductive loads.</td>
<td></td>
</tr>
</tbody>
</table>
In the followings, we discuss the structure and operation of low voltage mechanical switches, including contactor selection. We treat the semiconductor switches only shortly.

### 5.1. Mechanical switches
Regarding their structure and operation, the low voltage mechanical switches can be classified as biased, rotary, toggle switches and contactors. The switches in the first three groups can be operated manually, or automatically by another device. Contactors however, are self-operated, usually by a built-in electromagnet. Mechanical switches have three main structural components:

1. Switching mechanism (main and auxiliary contacts, arc quenching mechanisms),
2. Actuator,
3. Detent or arresting mechanism. With contactors, the operating electromagnet is responsible for the task of keeping the contacts in switched-on position.

5.1.1. Biased switches

A biased switch is one containing a spring that returns the actuator to a certain position. Biased switches can be operated by a pushing or pulling force, which opens or closes the contacts. Figure 6.73 provides an overview of their structure, of their operation principle, and plots the variation of their operating force versus translational actuator movement. By exerting a force $F_r$ on the actuator along the length $\delta$, first a normal closed (NC) contact pair opens, and later a normal open (NO) contact pair closes. In the resting position ($\delta=0$), the contact spring between the contact bridges and the operating spring are compressed, and the forces $-F_c(0)$ and $+F_o(0)$ act on the actuator. Namely, in the closed position of the NC contacts, $-F_c(0)$ ensures the necessary pressing force. The force $F_r$ linearly increases from an initial value $F_r(0)$ until the switch closes ($\delta=6$ mm). By pressing the actuator, the contact spring force $F_c$ starts to decrease linearly, and at the moment when the NC contact opens ($\delta=2$ mm), it instantly drops to zero. That is, at this moment, the force of the pre-stressed contact spring ceases, and remains zero until the NO contacts start to close ($\delta=4$ mm), resulting in a positive force from the pre-stressed contact spring that suddenly appears on the actuator. From this moment on, $F_r$ starts to increase linearly up to the closed position of the switch. The sum of the $F_c$ and $F_r$ provides the resulting force $F_r$, as the diagram indicates in the figure.

It is not enough to consider only the forces, because the fast operating time (in some specific cases 2...3 ms) of biased switches is also important when the switch is automatically operated.

![Fig. 6.73. Structure of biased switch, and its forces](image.png)

The rated current of biased switches is usually $I_r=10$ A. With smaller currents, probably at lower voltages, or with more contacts connected in series, the simple pressing contacts are not reliable enough, because the smaller voltage cannot cause a breakdown in the thin surface films, or the de-oxidation effect of the arc cannot take place. Sometimes the method depicted in Fig. 6.74 is applied to remove the thin film layer. In the open position (Fig. 6.74 a), the moving contacts are tilted until they reach the stationary contacts (Fig. 6.74 b). During closing operation, the moving contacts turn, and meanwhile, they slide on the stationary contacts until they arrive at the closed position (Fig. 6.74 c).
Manually operated biased switches are called push buttons. Regarding their function, automatically operated biased switches can form auxiliary contacts, or position switches (e.g. limit switches). Figure 6.75 shows the drawings of an auxiliary contact (a), a push button (b), and a limit switch (c).

![Fig. 6.74. Method to break up contact film](image)

Biased switches are almost always used only in control and signal circuits. If auxiliary contacts control electromagnets, the switch can be selected, and their durability can be determined according to the AC-15 and DC-13 utilization categories of table 6.2 and 6.3, and considering the data the manufacturer provides.

### 5.1.2. Rotary switches

The switching positions of rotary switches have to be definite. Therefore a rotary switch has a *detent mechanism* to arrest the movement in one active position rather than let the switch stall in an intermediate position. An example of such a mechanism, together with the contact pairs of a cylinder switch is shown in Fig. 6.76. A spring 2. pushes a reel 3. mounted on a lever 4. between the cogs of a notched wheel 1. fixed to the axle. The pressing force of the reel is balanced by the reaction forces in the normal directions $n'$ and $n''$. The axle can be moved from this $(n^n)$ rest position only by exerting an external momentum on it. If this happens, the side of the notch opposes the rotation first, and over the top of the notch it helps the rotation. In Fig. 6.77, the thick, continuous line shows the variation of the momentum of the detent mechanism, the thin line shows the momentum of the contacts, and the dashed-dotted line the resulting momentum (on the operating axle) between the $n^n$ and $(n+1)^n$ rest positions, when the momentums of the contacts and the detent mechanism are appropriately coordinated. The resulting momentum has three zero points, and the switching positions are definite. If the momentums are not adjusted appropriately (too high momentum of the contacts), the curve of the resulting momentum might cross zero at multiple points at the decreasing section, between the tilting point and the $(n+1)^n$ rest position. This can result in an indefinite position. If contact separation occurs during the declining side of the notch, then the resulting momentum is independent from the operator, and helps fast arc quenching by accelerating the separation. High power rotary switches exploit this effect. Moreover, sometimes a separate spring mechanism ensures fast contact opening independent from the external operating force.
Concerning their structure and operation, rotary switches can be classified into two groups:

1. The **rotary contact** switches (drum switches, switch cylinders, packet type switches) belong to one of these groups. With these switches, a contact piece turning between a pair of stationary contacts make or break the circuit. Therefore, contact is made at two points, where moving and stationary contacts meet.

2. **Cam operated** switches form the other group of rotary switches. They make and break the connected outputs in required sequence by either opening or closing circuits with a set of contacts operated by a rotary cam. The set of contacts can be single contacts or biased type switches with double breaking points.

### 5.1.2.1. a.) Rotary contact switches

The sketch of a **drum switch** can be observed in Fig. 6.78. It is a switch, in which the moving electrical contacts 2. are made on pins, segments, or surfaces on the periphery of a rotating cylinder 1. The stationary contacts 3. are held by spring 4. pressure against the revolving contact surfaces. These devices have been used for the simultaneous opening and closing of more circuits, for instance for motor starting or motor control. In newer versions – in switch cylinders – the rotating conductors are fixed to an insulating axle. A typical contact arrangement of such a device is shown in Fig. 6.79. These devices are used mostly for the switching of grouped circuits or to accomplish switching programs.
Packet-type (pacco) switches consist of a group of contacts, a mechanism that moves the contacts and secures them in a particular switching position, and a housing. The contact system of packet-type switches consists of separate sections (packages), each of which has an insulating plate with fixed contacts in the form of blades and also movable spring contacts that are insulated from one another. Figure 6.80.a shows one section, whereas Fig. 6.80.b shows an assembled switch having four sections. The fixed contacts are embedded in the insulating plate. Insulating wheels and bronze spring plates form the rotating part, which turns by $\pi/2$ with every switching operation. Due to an arc, gas develops from the insulating plates, thus helping arc quenching by blowing and cooling the arc channel. The switching position is ensured by a detent mechanism. By changing the shape, position and connections of the contacts, several different functions can be accomplished, therefore these units are widely used in the rated current range of 16...100 A.

**5.1.2.2. b.) Cam operated switches**

Cam operated rotary switches make and break the connected outputs in required sequence by either opening or closing circuits with a set of contacts operated by a rotary cam. The cam, which closes and opens contacts, has rotary movement and multiple positions, allowing multiple circuit functions controlled through a single operation. With appropriate cam design, different switching functions can be easily achieved. The principle applications are for making, breaking and isolation of power circuits and switching the auxiliary circuits. The notched cam of these devices closes or opens single or double break contacts. A typical example of a cam operated switch with double break contacts is shown in Fig. 6.81. This type of device is used up to a rated current of 250 A, and can be installed into switchboards as well. The flexibility in the contact block selection, and options to select number of contacts, ensures that a right switch can be chosen for the application intended. This switch thus offers design flexibility to assemble complex switching programs. Cam switches can be used as main switches to connect and separate low voltage circuits, and also to operate asynchronous motors with utilization categories of AC-2 and AC-3 (see table 6.2).

**5.1.3. Snap action switches**

With rotary switches, only complex mechanisms (detent mechanism, or spring force mechanism) can guarantee fast separation of contacts. In case of snap action switches, fast contact opening results from their operation principle, therefore the application of special mechanisms is not necessary. The advantage of snap action
switches is their simple structure, although their rated current cannot be more than 10 A. Regarding their structure and operation method, we distinguish rocker and tumbler switches.

### 5.1.3.1. a.) Rocker switches

Figure 6.82 shows the structure and operation of rocker, toggle switches. A spring and a sustaining cog together ensure the closed position of the contacts. If the rocker actuator is moved to an opposite position, the sustaining cog gets close to the pivoting point of the contacts, resulting in reduced torque acting on the closed moving contact. As the cog’s end point gets in line with the pivot point of the contact and of the rocker actuator, this torque becomes zero. After the sustaining cog passes this point, an opening torque occurs and the moving contact opens fast, independently from the operator, who has pressed the button. Finally the switch gets to the open position, indicated by dashed-dotted line in the figure. The closing operation is similar, but in the opposite direction.

![Rocker Switch](image)

**Fig. 6.82. Rocker switch**

Figure 6.83 presents the variation of the opposing torque acting on the rocker actuator as function of rotation angle. It can be observed that in the frictional dead zone, the pressing force on the contact and the movement of the contact temporarily cease. This frictional dead zone cannot be eliminated, although it can be reduced with smaller distance between the contact pivot point and the path of the sustaining cog. Because of this disadvantage, this switch type can be used only for switching small currents.

![Moment of Force](image)

**Fig. 6.83. Moment of force during opening of a rocker switch**

### 5.1.3.2. b.) Tumbler switches

Tumbler switches are widely used in home lighting and other applications worldwide as toggle switches. The sketch in Fig. 6.84 helps to understand their operating principle. The upper (driving) lever is operated manually, and the lower (driven) lever moves the contacts. The compressed spring situated between the two levers presses the levers onto the arresters in rest position. By turning the upper lever, the mechanism reaches a dead point, when the work point of the spring on the upper lever gets in line with the axis of the lower lever. At this point only a lengthwise force acts on the lower lever. After further travel of the upper lever, an opposite torque occurs at the lower lever and it flips fast to the opposite side, where the arrester stops it. The process is fast, and the opening or closing force is independent from the operator.

![Tumbler Switch](image)
The drawing of a tumbler switch with a single compressing spring is shown in Fig. 6.85. The fixed contacts on the opposite sides are connected or separated by a moving contact bridge at the driven lever or arm (double breaking contact). The dead zone therefore does not influence the pressing force on the contacts, as it can be followed in Fig. 6.86.

Micro switches are special snap action switches. Their operation is similar to that of tumbler switches. By applying an external force on their actuator, their contacts close, they trip the circuit. After releasing the actuator, the contacts get back to the rest position. Figure 6.86 shows the inside of a micro switch. A long flat spring is hinged at one end of the switch and has electrical contacts on the other. The curved parts of the spring at both sides exert a stretching force on the middle, flat spring. During operation, an actuator nub presses on the flat spring. The position of the fulcrum of the stretched springs relative to the flat spring determines the position of the contacts at the end of the spring.
Structure and operation of electrical switching devices

The defining feature of micro switches is that a relatively small movement (some tenth of mm) at the actuator button produces a relatively large movement at the electrical contacts, which occurs at high speed (regardless of the speed of actuation). With the micro switch in Fig. 6.87, the actuator is operated by a wheeled lever. The possible movement of the lever can be some millimeters with this solution. Considering that the switching time of these switches is around 1...5 ms and the bouncing time is 1...2 ms, 50 switching operation can be permitted with these devices in one second.

5.1.4. Contactors

The mechanical contactor is a special load break switch. Usually, an electromagnet provides the driving force to close its contacts; therefore it has special construction and tasks. Before we treat the structure and the operation principle of these switching devices, we have to mention that contactors are suitable for remote controlled switching operations. They are capable of frequent operation (up to 1200 sc/hour) and have long mechanical and electrical durability (max. 10⁷ sc). The applications of LV contactors cover a wide range of rated current (at rated voltage of Vₚ =400 V, Iₚ =4...1000 A), and can be used for all kind of utilization categories (see Tables 6.2 and 6.3). They are especially important in switching of motor circuits, namely in utilization categories of AC-2...AC-4 and DC-3...DC-5. The control and protection of LV electrical motors are almost always accomplished by contactors equipped with protective units (motor protective switch) or by contactors controlled by protecting devices. An exception is the application of semiconductor contactors and the switching of large and rarely switched motors. In these cases, the protection is provided by circuit breakers. Contactors can replace manually operated switches, and electromagnet operated relays as well. Consequently the largest group of switches is the group of contactors.

Concerning these properties, we discuss the structure and operation of low voltage electromagnet operated contactors. In the section „Overload protection of motors“, we deal with contactors used for the control and protection of three-phase squirrel cage asynchronous motors. Finally, we explain the selection method of contactors applied for the control of three-phase asynchronous motors.

5.1.4.1. A.) Structure and operation

Many types of low voltage electromagnet operated contactors have been manufactured. Figure 6.88 shows a simplified picture of one type, in which a single-phase AC electromagnet controls the three poles of the main contacts. The fixed yoke of the magnet is equipped with shorting rings, in order to prevent acoustic noise. The electromagnet provides a pulling force, and the translational motion of the moving part closes or opens the double breaking contacts. This type of construction is used for switching both DC and AC circuits, although recently, the main contacts are placed behind the fixed yoke, instead of behind the moving component of the electromagnet. The main structural parts of contactors are the current path, the mechanical components, and the auxiliary contacts. We explain these and the operation with the help of Figures 6.89….6.91. The main contacts are situated behind the moving part of the electromagnet in the schematic diagram of Fig. 6.89. The contactor of Fig. 6.90 is similar, although it includes an arc chute as well. The axonometric view in Fig. 91 shows a contactor, in which the main contacts are situated under the fixed yoke of the electromagnet.

![Fig. 6.88. Simplified drawing of a contactor operated by a pulling electromagnet](image-url)
The **current path** of each pole includes a pair of fixed (2) and a pair of moving (3) contacts situated between the connecting terminals (1), possibly a separate arcing contact, and an arc chute (4).

1. The **connecting terminals** (1) are usually bolted clamps for wires at smaller rated currents. With higher currents, the terminals are flat bars with through-bolts to mount cable clamps.

2. During closing operation, the **main moving contacts** (3) hit the **fixed main contacts** (2) with a high speed (max. 1.5 m/s). Therefore, bouncing has to be reduced. The heat of the arc practically removes the oxides from the surface, but this process has to be improved by choosing contact materials capable of auto-cleaning (e.g. AgCdO or AgSnO) or by applying self cleaning contact mechanism (see Fig. 6.74).

3. In order to prevent the arc from deteriorating the conducting properties of the main contacts, with higher rated currents ($I_r \geq 160$ A, AC), separate **arc chute**s (e.g. WAg) are also included in the current path.

4. Contactors with high rated current and exposed to increased stress (utilization categories AC-4, DC-4 and DC-5) include **arc chute**s as well. The arc extinguishing chamber is very similar to that of the low voltage circuit breakers, only smaller, since in this case only load currents are to be interrupted. With AC contactors, the arc chute is formed by (copper or iron) deion plates, whereas with DC contactors, it is a narrow gap in an insulator. The arc extinguishing chamber is situated inside a heat resistant (e.g. ceramic) enclosure. The arc constrained into the arc chute by the magnetic force of the current path, sometimes with a blowout coil.
The frame and operating mechanism are part of the mechanical components.

1. All structural components are supported by the frame (5), and the frame makes possible the mounting of the contactor into a switchgear or on the vertical wall of a switchboard. The frame is usually made from thermosetting epoxy resin, or at high rated currents, from aluminum casting.

![Diagram of contactor components](image)

**Fig. 6.92. Air gap size versus opposing force in a contactor**

1. The electromagnet is the essential part of the operating mechanism. Its fixed part (6) is mounted to the frame, and its moving part (7) is connected to the contact bridge (8). In the unit of Fig. 6.91, the contact bridge is situated under the fixed part of the electromagnet together with the current path. The electromagnet must firmly pull in, if the operating voltage across its coil (12) reaches 85% of its rated voltage $V_{\text{rm}}$. It has to withstand 110% of the rated voltage without harmful overheating. The reset voltage of the electromagnet is $(0.1...0.7)\cdot V_{\text{rm}}$. The yokes of the single phase AC magnets are made of laminated iron, and to reduce noise, they are equipped with shorting rings (see Fig. 6.88). Demagnetizing air gaps reduce the adherence resulting from remanence. The yokes of DC electromagnets can be made from solid iron, and less current is enough to keep them closed. The contactors today ensure this capability. The guidance of the moving part has to withstand several millions of switching cycles. If the magnet is de-energized, the release spring (9) moves it into normal, rest position, and keeps it there. The pre-stressed (compressed) main contact springs (10) ensure the appropriate pressure of the contacts. When energized (a voltage appears across its coil) in the rest position, and the pulling force $F$ of the magnet surpasses the opposing force $F_{\text{op}}$ of the release spring and the auxiliary contacts ($F>F_{\text{op}}=F_{\text{off}}-F_{\text{aux}}$), then the moving part, together with the contact bridge and the moving contacts, starts to move. The moving part reaches the closed position – the contact bridge closes the fixed contacts – only if the relation $F>F_{\text{op}}$ is satisfied throughout the pulling movement, or, if it is not satisfied at some points, then the decelerating energy must be less than the previous accelerating energy input. To select an appropriate contactor, the relation between the opposing force and the air gap must be known. Figure 6.92 plots the opposing force characteristics $F_{\text{op}}(\delta)$ of a contactor. It is similar to the graph we have seen with biased switches in Fig. 6.73.

The auxiliary contacts (11) are operated together with the main contacts by the movement of the contact bridge.

**5.1.4.2. B.) Overload protection of motors**
Experience shows that overload is the major cause of low voltage squirrel-cage motor damages. The overload current is higher than the rated current $I_r$, and it can result in overheating and therefore damage of the electrical insulation. Regarding their duration, we distinguish short and long overloads.

![Fig. 6.93. Time functions of in-rush currents of a squirrel cage motor](image)

1. **Short overload currents** can occur during normal operation of the motors, for instance during starting, star-delta switching of three-phase motors, or dynamic breaking. We have seen in the introductory part of this chapter, that the in-rush current of squirrel cage motors (both in categories AC-3 and AC-4) can reach $I_{ir}=6\cdot I_r$ at the moment of starting. This current diminishes in time and tends to a steady state value, which equals to the rated current $I_r$ with rated load, or with the no-load current $I_o$ if there is no mechanical load on the output. Figure 6.93 shows in-rush current time functions (with $I_{ir}=5.5\cdot I_r$). Higher the mechanical load, longer the in-rush time ($t_{ir}=2...15$ s) and the temperature rise. The temperature rise is proportional to the time integral of the current square. Heat transfer to the environment is negligible during this short period, since the in-rush time is much smaller than the thermal time constant $T_m$ (of the order of hours) of the motors ($t_{ir}\ll T_m$). Therefore only frequent switching operations influence the temperature rise. However, considering the stress of the switching device, we have to take into account the short overloads both during switch-on and switch-off operations, since the overload current always exceed the rated current significantly.

2. **Long overloads** last for such a long time, which is of the order of the motor thermal time constant. Therefore, the temperature rise of the motors can reach a dangerous level in these cases. Several reasons can lead to long overload currents, like the mechanical overload of the motor, drop of the supply voltage, short circuit of the coil turns, phase loss, switch-on with the rotor blocked, etc. The increased current of frequent switching operations can also be classified as a long overload, if it can overheat the motor.

If the requirements are less strict, when overload practically does not occur, e.g. with motors of cooling fans, motors are not protected against overloads. In this case, the contactor’s task is only to turn the motor on or off. The electromagnet of the contactor can be energized simply by a rotary switch or by a rocker switch, although a more practical way is the **impulse control**. In case of impulse control, the switching operations can be accomplished by push buttons and the auxiliary contacts also play an important role in the operation. The circuit diagram of an impulse controlled motor can be observed in Fig. 6.94, in a simple case, when the motor does not have an overload protection, and fuses provide the protection against short-circuits. The motor can be started by pressing the button „On“ for a short time. This energizes the electromagnet, and the contactor pulls in. The NO auxiliary contact shorts the terminals of the „On“ button, keeping the electromagnet energized and the motor run, even after the „On“ button has been released. This self holding circuit can be broken by pressing the „Off“ button. The NC contact of this button opens the circuit, the electromagnet becomes de-energized and it removes the by-pass of the „On“ button. Therefore, after releasing the „Off“ button, the circuit can be turned on again by pressing the „On“ button. The advantage of this solution is that the motor can be operated from several different points, by parallel connected „On“ buttons, and serial connected „Off“ buttons. Further advantage is that in case of voltage interruption, the de-energized contactors do not turn the motor back automatically. If a phase-loss relay is also applied, its resting contact connected in series with the „Off“ button automatically turns off the motor, when the voltage of any of the phases interrupts. Without such a relay, the circuit in Fig. 6.94 provides protection only against the interruption of phase L3, since the electromagnet is supplied from that phase. If the magnet coil is connected to line to line voltage, then the loss of two phases can be detected by the circuit.
Overload protection can be accomplished, if the output contact of the protective relay is connected in series with the „Off” button or buttons. The protective relay might monitor the motor current or directly the temperature. If an overcurrent flows up to a specific time, or if the temperature reaches a pre-set threshold, then the overload relay trips the contactor control circuit, and disconnects the motor. Consequently, a contactor and a protective relay together provide an easy way for current or thermal protection.

There are two types of overcurrent protection: the thermal relay and the electronic protective relay. We note that the name thermal relay is improper, since the unit includes an electromechanical relay with a bimetallic strip. The input of both relays is the current of the motor.

a.) The protective characteristic curve of the thermal relay must comply with the requirements – regarding cold and hot initial conditions – of the standards. These requirements can be justified by physical considerations.

1. According to regulations, electric motors must be able to run at their rated power if their supply voltage drops by 5% from their rated voltage. Provided that \( \cos \varphi \) is constant, this indicates an increased current, around \( 1.05 \times I_r \). Since the thermal time constant \( T_m \) of the commonly used (small) motors is approximately 0.5 hours, the protective relay must not disconnect the motor even after a time of \( 4 \times T_m \) that is, after 2 hours has elapsed, no matter if the relay has been cold or hot before motor start. However, it has to trip the circuit within 2 hours at \( 1.2 \times I_r \), or within 2 minutes at \( 1.5 \times I_r \).

2. During motor starting, the in-rush current must not trip the thermal relay. Regarding Fig. 6.93, we have seen that the temperature rise is proportional to the time integral of the square of the in-rush current. Consequently, the time function of the rate of the equivalent motor current \( I_{eq} \), and the rated current:

\[
\frac{t_{eq}}{t_r} = \sqrt{\frac{1}{T} \int_0^t \left( \frac{l_{eq}}{l_r} \right)^2 dt},
\]

(6-11)

where the equivalent current \( I_{eq} \) is a constant current that would cause the same temperature rise as the in-rush current during the duration of the in-rush current.

If the curve representing this current is below the characteristic curve of the thermal relay, the relay will not trip. This case is indicated in Fig. 6.95. In case of frequent starting and stopping, when the motor cannot cool back between two start-ups, the sum of the equivalent currents from formula (5-13) provides the resultant time function. According to the standards, the initially hot thermal relay must not trip within 2 seconds at \( 6 \times I_r \). The cold and hot characteristic curves of a thermal relay appropriate for the protection of squirrel cage asynchronous motors are plotted in Fig. 6.96.
Fig. 6.95. In-rush currents and characteristic curve of a thermal relay

Fig. 6.96. Characteristic curves of a thermal relay

1. Currents higher than the in-rush current can occur only in case of faults. This current range is indicated in Fig. 6.96, and it is clear that a thermal relay cannot provide such short disconnection time within which the motor and/or the thermal relay itself remain undamaged. Short-circuit protection can be accomplished by a circuit breaker (including MCB) or by a slow fuse. Figure 6.97. shows the equivalent motor current, and the characteristic curves of a thermal relay, a fuse, and a circuit breaker together in one diagram. The characteristic curves of the thermal relay and the CB in the overload range are identical. It can be clearly seen that the fast tripping characteristic of the CB is more appropriate for the motor starting than the curve of the fuse. Therefore, the combination of a compact circuit breaker and a contactor connected in series is used for motor protection recently. The current limiting circuit breaker provides protection against both overloads and short-circuits. A separate thermal relay is not necessary, and the sole purpose of the contactor is to make the remote operation of the motor possible.
Thermal overload relays have to monitor all the three phase currents, therefore they include three separate bimetallic strips inside a plastic housing. The phase currents heat these strips. Due to an overload in any of the strips, the bimetal bends enough to be able to push a slide bar, which trips a latching mechanism. By releasing the latch, a spring snaps an NC output contact into open position. The structure of a thermal overload relay can be observed in Fig. 6.98. After operation, if the bimetallic strips have cooled back to an appropriate temperature, the mechanism can be reset by a button. With other relay types, the reset button can be automatic as well. The tripping current of the overload thermal relay can be set by a rotary or slide switch.

With asynchronous motors operated in star connection, the inputs of the thermal relay must be inserted in series with the phase conductors at the supply. This connection method can be used with delta connection as well, although it is a much better solution, if the bimetallic strips detect the current of the motor coils directly. The same holds true for motors with star-delta starters, since they run in delta connection permanently. In this case, the tripping current of the relay must be set to $\sqrt{3}$ times of the current valid in star connection. No matter if the relay is installed in the supply circuit or in the circuit of the motor coils, its inputs are connected in series to the main terminals of the contactor. Up to a rated current of $I_r = 35$ A, this is accomplished by direct connection of the overload relay and contactor main terminals. With higher currents, current transformers provide the current for the overload relay. These are secondary relays, as their rated current is less than that of the motor to be protected.

A contactor and an overload relay together (possibly with a current transformer) is usually called motor protective switch. This must not be confused with compact circuit breakers designed for motor protection. Besides the overload protection, contactors can be equipped with other components. We give an overview about some of them in the followings:

1. The pneumatic timer (time relay) provides a delayed operation on its output contacts after the closing or opening of the contactor. Depending on the unit type, the delay can be set in the range of 0.3 ... 180 s.
2. Energy saving operation can be accomplished by an electromechanical latching unit (self holding). After energizing the electromagnet, this unit keeps the contactor in closed position even if the supply voltage is disconnected from the magnet coil.

3. Time relay to delay the change from star to delta connection. Time setting: 2...24 s.

4. Mechanical interlock can inhibit the simultaneous operation of two contactors. This can replace electrical interlock circuits.

5. Interface to convert low level electrical signals (e.g. from computers or electronic devices) into AC voltage having appropriate power for operating an electromagnet.

We discuss three basic circuits appropriate for the switching of three-phase asynchronous motors, and including overload protection. The overload protection is based on monitoring the motor current.

In the first case, the impulse controlled circuit of Fig. 6.94 is complemented with a thermal relay (Fig. 6.99). In the other two cases, combinations of two and three contactors provide the control of the motor. The circuit in Fig. 6.100 is appropriate for the direction change and switching on or off three-phase motors. The direction of the rotation can be changed only, if the motor has been turned off previously by the "Off" button. This method is advantageous, because the arc between the contacts of the contactor can die out during the relatively long time of the switching process, therefore a possible fault is eliminated.

Figure 6.101 shows a circuit, with which the star-delta starting of motors can be accomplished. The main and control circuits are shown separately. Three contactors are used: the main contactor K, the contactor providing the star connection Y, and the contactor implementing the delta connection, denoted by Δ. By pressing the "On"
button, the motor starts in star connection, because contactor K connects the supply voltage across the coils after contactor Y has been energized. An interlock ensures that this can happen only if contactor Δ is off. At the same time, the NO auxiliary contact of the main contactor closes providing self holding for both contactors K and Y. Furthermore, the time relay TR starts. After the delay time is over, an NC contact of the time relay opens the holding circuit of contactor Y, and its NO contact closes and energizes contactor Δ. Again, an interlocking circuit inhibits the simultaneous operation of contactors Y and Δ.

Fig. 6.101. Contactor combination for star-delta starting

The operation method of the overload thermal relay implies that the temperature rise of the bimetallic strips reflects only the average temperature rise of the motor. Therefore, the hottest parts of the motor can remain without protection. Bimetallic strips heated indirectly can follow even the current proportional to the average motor temperature only with a delay. With indirect heating, the heat is transmitted from the heating wire to the bimetal through an insulating layer. Even in this thin layer, the heat conduction is so low that it can cause a delay in the temperature rise of the bimetal, when an overload occurs. If the load drops rapidly, the hot heating wire might heat the bimetal further, resulting in false tripping. Although the motor is not in danger, the protection disconnects it from the supply. Consequently, thermal relays are not appropriate for the protection of large motors and/or motors with frequently varying loads.

b.) Electronic motor protective relays help to eliminate the problems of thermal relays. One type of these devices can estimate the hottest temperature of the motor with relatively high accuracy, without any delay. The unit detects a voltage proportional to the highest motor temperature, therefore it is also said to be a simulation overload relay. The functional elements of this protective device are similar to other electronic relays processing analog signals. If the input is a current signal provided by conventional current transformers measuring the three phases, then a coupling unit at the input must convert this current signal into a voltage interpretable to the electronic component. State-of-the-art current transducers (e.g. with Rogowsky coil) can provide voltage signal directly, thus making the coupling unit much more simple. Besides, these current transducers can follow the current variation more precisely, thus they can measure in-rush current resulting from motor starting, or direction change much more accurately. This is necessary for the proper simulation of the temperature rise. If the analog voltage signal exceeds a specific threshold representing the hot point of the motor, then an electromagnet operated output relay opens an NC contact and breaks the circuit, which supplies the contactor controlling the motor. The same output relay operates when a phase losses, since the protective unit monitors the three-phase supply voltage with another input.

With the method of direct temperature monitoring, the detector elements must be installed directly inside the motor. Since temperature is measured directly, the detector can be a thermo-mechanical relay. Frequently used solutions are the micro bimetallic switch and thermistor relays. The first one is a cheap solution for the protection of small, single-phase motors, or connected in series, for the protection of three-phase motors. The second method is applied only for motors with substantial value or with motors playing a major role in a highly important technological process, where reliability is of primary importance. In both cases, the detectors are built into the motor coils.
a.) Micro bimetallic overload relays are very simple and cheap devices, which do not require any voltage supply (see Fig. 6.7). These units directly break the motor circuit of small single-phase motors, or the self-holding circuit of a contactor. They are rarely used for the protection of three-phase motors, because of their disadvantages. The heat capacity of the large relays are high, therefore they cool back to smaller temperatures only slowly. This delays the reset, and the restart of the motor. Furthermore, their thermal coupling with the motor is not adequate.

b.) The temperature detector elements of thermistor relays are much smaller than micro bimetallic switches. Therefore – and because of their material – their heat capacity is also smaller. To protect the motor, the NC output contact (terminals 11 and 12 in Fig. 6.9) of the thermistor relay has to be connected in series into the self-holding circuit of the contactor. After pressing and releasing the button V of the relay, the motor can be started. But only if its temperature is smaller than the rated response temperature $T_{sense}$ of the thermistor (see Fig. 6.8). If the motor temperature surpasses this value during operation, then relay K releases and opens the contactor circuit.

5.1.4.3. C.) Selection of contactors

During contactor selection, first of all, we have to stick to the general rules of switching device selection. It is especially important to determine and verify the lifetime of contactors, which switch currents much higher than the rated current of the controlled circuit. We treat this selection method only for the case of three-phase asynchronous motors, which is the most frequent task, for which contactors are used.

The lifetime or durability of a contactor is given in switching cycles (sc). This lifetime depends on:

1. the utilization category (in our case, AC-2, AC-3, and AC-4 in table 6.2),
2. the rated power $P_r$, or rated current $I_r$, of the motor to be controlled (which depend also on the utilization category and the rated voltage $V_r$ as well), and
3. the switching cycles per hour (sc/h).

The manufacturers provide a wide range of contactor types, and they give the data for device selection in catalogs. Contactors can be selected based on these data.

![Fig. 6.102. Durability curves](image)

The thick, continuous line in Fig. 6.102. shows the durability characteristic curve of a given contactor type. The diagram is valid for a given utilization category, a specific rated voltage, and given switching cycles per hour. It represents the lifetime $D$ of the contactor as function of the motor power $P_r$ to be switched. Sometimes, instead of power, the motor current $I_r$ is indicated. Region a of the curve represents the possible maximum switching cycles without electrical load, in other words, the mechanical durability $D_{mech}$ of the contactor. Section c indicates the possible maximum power that the contactor can switch. No durability can be given for this power.

We note that the manufacturers often include $P_{max}$ in kilowatts in the contactor type names to distinguish the different contactor versions in the most frequently used AC-3 utilization category and with rated voltage $V_r=400$ V ($P_{max}$). If the power of the motor to be switched is less than $P_{max}$, then the contactor durability is defined. Higher the power, smaller the durability, as section b clearly shows. If the rated voltage is different, then sections b and c are both shifted. If only the utilization category and the switching cycles per hour differ from the values of the diagram, then section b has to be modified (see dashed curves).
Durability selection can be simplified, if the durability curves (valid for given rated voltage $V_r$) of the contactor types are provided as function of the switch-off current $I_{\text{off}}$, instead of as function of the rated motor power $P_r$ or the rated motor current $I_{\text{r}}$. The switch-off current $I_{\text{off}}$ equals to the corrected rated current $I_{\text{rcor}}$ of the motor with utilization categories AC-2 and AC-3 ($I_{\text{off}}=I_{\text{rcor}}$). With category AC-4, a corrected current of $I_{\text{off}}=6 \cdot I_{\text{rcor}}$ has to be taken into account. Figure 6.103 shows a similar set of curves valid at the voltage of $V_r=400$ V. The numbers (4...132) indicate the values of $P_{\text{max}}$ in kilowatts, and these indicate the contactor version types as well. Two numbers 2, 2 and 4 show two versions of the second type. With version types 4...18, 5, the dashed lines are valid for the utilization category AC-4.

Depending on the switching cycles per hour and on the utilization category, the manufacturers provide a correction factor $k$ as a percentage value, as is shown in Fig. 6.104. The value of $I_{\text{off}}$ can be determined with this factor by the following formula:

$$I_{\text{rcor}} = \frac{100I_{\text{off}}}{k}.$$  \hspace{1cm} (6-12)

It can happen that a contactor is used in mixed mode that is, for instance both in categories AC-3 and AC-4, but the use in AC-4 is only a fraction $p\%$. If the durability of the contactor is $D_1$ in AC-3, and it is $D_2$ in AC-4, then the durability in mixed mode:

$$D_m = \frac{D_1}{1 + \frac{p}{100} (\frac{1}{D_2} - 1)}.$$
5.2. Semiconductor switches

In the previous chapters, we have seen that mechanical switches have some unfavorable features, which result from the electrical, thermal and mechanical stresses occurring during their operation. The bouncing of the contacts during switch-on, the degradation of contacts due to the arc, the relatively long operating time, and the limited durability depending on the utilization and on the rate of switching, all limit the applications of mechanical switching devices. The lifetime of semiconductor switches having no mechanical contacts is practically unlimited, and they can eliminate the other unfavorable effects as well. Their further advantage is that they can be applied in explosion hazardous or in aggressive chemical environment as well. However, the significant forward voltage across them, and consequently their high loss resulting also in cooling problems is their major disadvantage. Furthermore, it has to be taken into account that they cannot galvanically separate the load when switched off; namely a small reverse leakage current always flows in this state.

Semiconductor switches can turn on or off electrical circuits by controlling the conductivity of semiconductor elements. They are appropriate for all the general tasks of a mechanical switching device. Their major field of application is motor control; therefore they have to satisfy the special requirements valid for contactors. Thus, they are also said to be semiconductor contactors. These units may include mechanical switching elements as well in their auxiliary or control circuit, but the main circuit is controlled by semiconductor elements.

The semiconductive elements of these switching devices are usually thyristors, and bidirectional triode thyristors or TRIACs. The thyristor is a four-layer, three terminal semiconducting device with each layer consisting of alternately n-type or p-type material. The main terminals, labeled anode and cathode, are across the full four layers, and the control terminal, called the gate, is attached to p-type material near the cathode. Conduction can be triggered by a voltage applied at the gate. This voltage has to be positive with respect to the cathode. The five layered TRIACs are able to conduct current in both directions; therefore they are used for switching AC currents. They are approximately equivalent to two complementary unilateral thyristors joined in antiparallel and with their gates connected together. They can be triggered by either a positive, a negative or alternating positive and negative voltage pulses in each half cycle.

Semiconductor switches can switch DC or AC currents. When the control signal disappears, the AC current ceases in its next current zero. However, when controlling DC loads, a turn-off circuit must ensure the interruption of the current. The structure of semiconductor switches significantly differs in DC and AC applications. In case of AC, the three-phase and the single-phase units also differ. We shortly describe the AC semiconductor switches in the followings.

We have to note that thyristors in semiconductor switches need appropriate overvoltage and overcurrent protection. The proper selection and adjustment of protective equipment – like surge arresters, R-C elements, fuses, etc. – are essential. The operation of thyristors itself, and other switching processes can result in harmful overvoltages across the switch terminals. Overvoltages, overload and fault currents may easily damage the semiconductor elements.

![Control circuits and current time functions](image)

**Fig. 6.105. Control circuits and current time functions**
AC semiconductor switches differ in the arrangement of the semiconductor elements in the main circuit and in their control signal. Figure 6.105 shows circuits controlled by a constant DC voltage. In the circuit of Fig. 6.105.a, antiparallel thyristors, whereas in Fig. 6.105.c, a TRIAC switches the main circuit. By closing the switch K, a triggering current impulse \(-i_{G1}\) or \(i_{G1}\) and \(i_{G2}\) makes the semiconductor switch conduct, and the AC current starts to flow in the main circuit. In the diagram of the figure, we assume an ohmic load. With antiparallel thyristors, the rms current flowing through each thyristor is \(1/\sqrt{2}\) times the rms current in the main circuit. During switch-off, after the triggering impulse disappears, current still flows in the main circuit up to its next zero. The current time functions during switch-on and switch-off processes can be observed in Fig. 6.105.c. We note that the semiconductors can be triggered by rectified DC signal or by an impulse from a medium frequency generator as well.

After a thyristor has been switched off, a finite time delay must elapse before the next trigger. This delay, the commutated turn-off time \((t_q)\) limits the switching frequency of semiconductor switches. With fast thyristors \((t_q \leq 20 \mu s)\), this frequency limit is 20-25 kHz. By adjusting the time instant of switch-on of an inductive circuit, the transient component can be completely eliminated that is, current surges can be limited.

In case of single-phase loads, usually only the phase conductor is switched by a semiconductor switch. In order to galvanically separate the load from the supply, a disconnector should be connected in series with the semiconductor switch. Because of the great (1…2 V) forward voltage of the thyristors and TRIACs, conducting high currents goes hand in hand with significant loss. This loss appears as dissipated heat; therefore the cooling of the switching device has to be solved. If the duration of a continuous operation is of the order of hours, or if the cycle time of an intermittent duty is long, then it is worth connecting a mechanical switch parallel to the semiconductor switch. In this case, the utilization category of the mechanical switch is AC-20. It can be switched on only after the switch-on of the semiconductor switch, and it has to be open (arc free) before the removal of the trigger signal from the thyristors. Figure 6.106 shows a thyristor switch equipped with a disconnector (D) and a parallel mechanical switch (K).

The transient DC component of the current can be eliminated during the switch-on of three-phase motors or other three-phase inductive loads as well. When switching off, the phase current reaching the current zero first, will be interrupted first. After this moment, the line-to-line voltage maintains the current of the other two phases, and this current breaks after a time of \(\pi/2\omega\) has elapsed. The connection of a three-phase thyristor switch together with a disconnector (D) in a circuit can be seen in Fig. 6.107.
6. Switching device combinations

Switching device combinations serving the tasks of two or three basic devices at once are widely used nowadays, first of all in in-door switchgears. For a reasonable price, device combinations are easy to install and need less installation space than separate units. Manufacturers do not have to apply separate regulations of all the basic devices, since the standards specify the requirements of all possible combinations.

The device combination types can be classified into two groups:

1. The manufacturer assembles serial connected switching devices in a single unit. This does not really result in new device types; only the on-site installation work becomes simpler. The basic switching devices are easily recognizable in these units; therefore it is not necessary to discuss them in details again. The protective characteristics of the fuses, switches, and circuit breakers included in these combined units, have to be adjusted appropriately.

2. New constructions made from basic switching devices and forming new stand-alone equipment. Such disconnector combinations are widely used in medium voltage switchgears, but they are applied more and more in in high voltage systems as well.

The combination of a circuit breaker and a disconnector in a single unit belonging to group a) is also prevalent in high voltage systems. We present some medium and low voltage device combinations in the following section.

6.1. Medium voltage switching device combinations

Disconnected type device combinations are prevalent primarily in such places, where the probability of fault occurrence is low. Using a circuit breaker is not always economical. A CB can be replaced by a device that can interrupt operating currents, plus it can provide isolation as well. Equipped with a fuse, the problem of short-circuit protection can be solved as well. Since all these device combinations include a switch, it is worth summarizing the requirements specified for switches. For general purpose, high and medium voltage switches the standards specify the current breaking and making capacity. We present six of the eleven current breaking capacity types:

1. Breaking capacity of active circuits: if $\cos \varphi \geq 0.7$, then $I \leq I_r$ ($I_r = 200, 400, 630$ A).

2. Breaking capacity of ring circuits (e.g. busbar rings connect two active network parts, and after interrupting the ring current, both parts remain energized): with $\cos \varphi = 0.3$ and if $V_r = 0.25 \cdot V_r$, $I = I_r$ .

3. Breaking capacity of no-load transformers: With $I_r = 200$ A, $I = 6.3$ A; with $I_r = 400$ A, it is $I = 10$ A; with $I_r = 630$ A it is $I = 16$ A.


Short-circuit making capacity: depends also on the drive of the switch (e.g. with manual drive $I < 7.5$ kA).

One pole of a three-phase, indoor switch-disconnector belonging to group b) and having an arc chute with narrow gap can be seen in Fig. 6.108. The moving arcing contact is situated between the main contact knifes, and it is connected to the fixed contact inside the narrow gap arc chute when closed. The arc chute is made of epoxy and it is open at the bottom. During switch-off, the main contacts open first, and after they are separated, the arcing contacts open. Contact separation is very fast, and the arising gases help to extinguish the arc. Fast movement is ensured by a pre-stressed spring fixed to the operating shaft.
The switch-disconnector-fuse in Fig. 6.109. is also an indoor construction. Its switch-disconnector belongs to group b), and it is equipped with a fuse. In case of a fault, the striking pin of the fuse operates the switch-disconnector. Because of the high tolerance of fuse characteristics, faults might cause a major problem, if current still flows in the healthy phases. For instance, when a three-phase short-circuit occurs, one of the fuses interrupt the current faster than the others, and at the same time it triggers the opening of the switch. In order to prevent a failure, the other two fuses must operate before the opening process starts. This condition can be satisfied, if the opening time of the switch-disconnector is longer than the time delay resulting from the non-equal fuse characteristics. If the switch disconnector is equipped also with an overload release, the characteristics must be coordinated. This coordination is shown in Fig. 6.110. Point $P$ is the intersection of the boundary curves belonging to the outermost lower tolerance of the overload release and the higher tolerance of the fuse. The current belonging to this point is the most critical, since this is the highest current that the switch-disconnector must be able to interrupt.

### 6.2. Low voltage device combinations

We have already seen low voltage device combinations when we discussed motor protecting equipment. These were the combination of a contactor and a thermal relay and the combination of a circuit breaker and a contactor, but the integrated direction change and star-delta starter units belong to combined devices as well.
In the following section, we treat other device combinations. Their possible variants can be classified into the two groups mentioned previously with MV device combinations (see Table 6.4). The devices in group a) include a fuse connected in series with another switching device. In these composite units, the basic devices are easily recognizable, thus it is unnecessary to discuss their structure and operation again. The characteristic curves of their protective units – like fuses, circuit breakers, or overload releases in switches – have to be selected appropriately (see Fig. 6.110.). The second column of Table 6.4 lists device combinations belonging to group b). These are new, stand-alone constructions made from two or three basic switching devices or from a basic device and other components. We review their structure and operating principles in the following section.

Table 6.4

<table>
<thead>
<tr>
<th>a.) Switching device and fuse in series, forming a single unit</th>
<th>b.) New construction made from two or three basic switching devices</th>
</tr>
</thead>
<tbody>
<tr>
<td>Disconnector-fuse</td>
<td>Fuse-disconnector</td>
</tr>
<tr>
<td>Switch-fuse</td>
<td>Fuse-switch</td>
</tr>
<tr>
<td>Switch-disconnector-fuse</td>
<td>Switch-disconnector</td>
</tr>
<tr>
<td>Integrally fused circuit-breaker</td>
<td>Fuse-switch-disconnector</td>
</tr>
</tbody>
</table>

The fuse-disconnector is one of the oldest, and nowadays only rarely used device combination. It is a disconnector, in which one or more poles have a fuse in series in a composite unit. A lid includes blade type fuse links. When the lid is closed, the knives of the fuse links enter the fork shaped fixed contacts of the fuse holder. Consequently, the moving contact is the fuse link itself. The advantage of this mechanism is that the three phases can be switched simultaneously, and it ensures the safe replacement of the fuse links after the contacts are open. Its disadvantage is that a switching operation must not be permitted, when current is flowing through the contacts.

Fig. 6.111. Cross sectional view of a switch-disconnector

The fuse-switch is similar to the fuse-disconnector, but a spring drive executes the switching operation. There are two contact points between the moving contacts (the knives of the blade type fuses) and the fixed contacts in each pole. Deion plates help extinguishing the arc. This device combination is also rarely used recently.
The base of a switch-disconnector is a disconnector, but equipped with arc chutes, sometimes even with arcing contacts. These units are regularly installed into rarely operated final circuits of metal enclosed switchgears. Switch-disconnectors belong to utilization categories AC-21 … AC-23 that is, they switch the currents of grouped loads. Figure 7.140 shows the cross sectional view of a switch-disconnector having a rated current of $I_r=250…1000$ A. The current path is situated between the connecting terminals (1). To extend lifetime, arcing contacts (2) are fixed onto the moving contacts, namely onto the disconnector knives (3). By precise adjusting, manufacturers ensure that the main moving and fixed (4) contacts separate first, followed by the separation of the moving and the fixed arcing contacts (5). The electrodynamic force constrains the arc into the deion plate arc chute (6), where it dies out. The metal deion plates distort the electric field distribution that is, reduce the dielectric strength between the open contacts. Therefore, to satisfy the requirements for insulation distance in disconnectors, the distance between the open contacts has to be increased. A spring mechanism provides the appropriate speed of the moving contacts, making it independent from the operating personnel. Figure 6.112 shows a modern, compact switch-disconnector, with rated current of $I_r=320…630$ A. These devices are appropriate for utilization categories AC-22 and AC-23, or by connecting the poles in series for categories DC-22 and DC-23. They are able to make short-circuit currents up to 50 kA peak. Their electrical durability in category AC-22 is 10000 sc, in the other categories 1000…1500 sc.

Fuse-switch-disconnectors are widely used devices in metal enclosed switchgears. They are suitable for the relatively frequent switching of load currents. A fuse provides the fault protection inside the unit, and the open
contacts provide safe isolation distance for replacing the fuse links. The cross sectional view of such a device can be observed in Fig. 6.113. A blade type fuse link (1) is inserted into a fuse holder (2). The contacts of the fuse holder form the moving contacts (3). One of these contacts is connected to the moving arcing contact (4). During switch-off, the moving bridge tilts around a pivot. First, the moving and fixed main contacts (5) separate on the left side, which is followed by the separation of the left moving and fixed (6) arcing contacts. Electrodynamic forces constrain the arc into the deion plate arc chute (7). After the extinction of the arc, the moving main contact on the right also separates from the fixed part, finally resulting in double isolation. During switch-on, the contact pairs close one after the other as well. Figure 6.114 shows a manually operated fuse-switch-disconnector. Three 00/100A...4/1600A blade type fuse links can be inserted into this device. The tilting mechanism is manually closed or opened during making and breaking of currents. These units are used in a wide rated current range ($I_r=100...1600$ A), in utilization categories AC-21 and AC-22 or DC-21 and DC-22. They can make short-circuit currents up to 25...50 kA rms, with an electrical durability of 100...300 sc.

7. Overvoltage protective devices

Overvoltage is any voltage between one phase conductor and earth or between phase conductors having a peak value exceeding the corresponding peak of the highest voltage for equipment (distribution networks, switchgears, other electrical components). It stresses the electrical insulation, and the degree of stress depends on the magnitude, the frequency and the duration of the overvoltage.

The task of overvoltage protection devices is to limit the overvoltages in electrical systems. They do not contribute to the operation of a system, they remain idle most of the time, when the voltage is under a specified limit. They cannot be operated on purpose, or manually, however, they must automatically operate if an overvoltage occurs in the system or equipment. Depending on their sources and duration, overvoltages can be classified into three main groups: internal overvoltage, atmospheric overvoltage, and overvoltage from electrostatic discharges.

1. **Internal overvoltages** are temporary or transient overvoltages in the system, resulting from a switching operation or from a fault in the system itself. Two types of internal overvoltages can be distinguished: Short, transient overvoltages from switching operations. Their duration is less than some milliseconds, they are aperiodic or fast decaying periodic voltages. Long duration overvoltages, generally having power frequency. Usually, asymmetric earth faults or resonance effects are their primary cause in low voltage networks.

2. **Atmospheric overvoltages** are independent from the operation of the electrical systems. They are caused by lightning strikes, but nuclear explosions have similar effects as well. They last up to some microseconds. Lightning strikes can result in overvoltages in the following cases:

3. Direct lightning strike into the phase conductor of an overhead line.

4. A lightning strikes the primary lightning protection system (lightning rod, grounding wire) of the equipment. The lightning current flowing into the ground through the earth resistance raises the voltage of the equipment across the earth resistance. This increased voltage can lead to a flashover.

5. Overvoltage can occur without direct lightning strike as well. It is enough if the lightning hits the ground in the vicinity of an overhead line or other electrical equipment, like building installations. Conductive, inductive or capacitive coupling can be responsible for these secondary overvoltages, which mainly risk low voltage equipment.

6. Electrostatic charge separation occurs when two materials contact each other and after contacting, they separate. Usually the friction of surfaces cause this triboelectric charging process and the charges remain if at least one of the contacting materials is insulating. The electrostatic charge accumulates on the insulator and can lead to a discharge, which can cause fire or explosion. Furthermore, the discharge can damage the insulation of electric apparatus leading to faulty operation. The electrostatic discharge (ESD) is always accompanied by steep, high magnitude current pulses.

We discuss only the most commonly used overvoltage protecting devices, but we do not treat complex overvoltage protection systems built from these elements. First, we deal with the overvoltage protective devices used in high and medium voltage networks.

7.1. High and medium voltage overvoltage protecting devices
Rod gap lightning arrester, expulsion type arrester and valve type arresters – recently replaced by non-linear metal-oxide resistors – are among the devices used in HV systems for protection against overvoltages. We present only the rod gap and the metal-oxide surge arresters here.

### 7.1.1. Rod gap lightning arrester

It is the simplest type of arrester. As Fig. 6.115 shows, it consists of two rods, which are bent at right angles with a gap in between. One rod is connected to the line to be protected and the other one to earth. When an overvoltage surge appears on the line, the gap sparks over and the surge current is conducted to earth. After the surge is over, the arc in the gap is maintained by the normal supply, resulting in earth-fault. This short-circuit current must be interrupted by a circuit breaker. The climatic conditions (e.g. rain, humidity, temperature etc.) and the polarity of the surge affect the performance of rod gap arresters, resulting in a wide tolerance of the spark-voltage. Because of these limitations, the rod gap arrester is only used as a back-up protection in case of main arresters, or as an arc deflecting unit to protect insulation.

### 7.1.2. Metal-oxide surge arresters

Conventional valve type surge arresters incorporate non-linear silicon-carbide resistors and a series of spark gaps in series, in a tight, porcelain container. The role of the spark gaps is to help interrupting the residual current (reaching some hundreds of amperes) maintained by the 50 Hz supply voltage after a protective operation. The relation between the electric field \( E \) and the current density \( J \) in a non-linear resistor is characterized approximately by the equation

\[
E = B \cdot J^\alpha,
\]

(6-14)

where the non-linearity factor \( \alpha \) is small (4...5) for conventional arresters. If no spark gaps were included, the non-linear resistors would be damaged by overheating in a short time. By raising the value of \( \alpha \), the residual current can be reduced, the characteristic curve more and more approaches the ideal curve belonging to \( \alpha = \infty \). High \( \alpha \) can result in such a small residual current that is not harmful for the non-linear resistors.

The ZnO composite ceramic is the result of a long research process in solid-state physics. The resistors of the surge arresters consist of 90 % ZnO ceramic base, and additives (bismuth-oxide, cobalt-oxide) form the remaining part. The solid arrester discs are made by compressing the dusty mixture of these components, and by exposing them to high temperature. During this process, the bismuth-oxide melts, and is converted to a glassy state. A very thin (~0.01 μm) bismuth-oxide layer forms between the 10...20 μm small ZnO grains. The diffusion of the cobalt-oxide into the ZnO makes the small grains relatively good conductors. The thin bismuth-oxide layer is responsible for the non-linear behavior, its surface acts like a p-n junction in a diode. With small electric field strengths, the bismuth-oxide impedes the motion of electrons, allowing only a small capacitive current through the arrester. By raising the field strength, as a result of the tunnel effect, the electrons start to flow through the grains, and the resistance of the arrester is determined by the resistivity of the ZnO grains. The current paths inside an arrester disc are formed by the series connection of the zinc-oxide grains.

The \( E-J \) characteristics of zinc-oxide and silicon-carbide surge arresters can be compared in Fig. 6.116. The diagrams are in log-log scale. By mirroring the graphs, the characteristic curves are valid for negative values as well. If we take the value of \( \alpha \) constant, the approximate equation (6-14) cannot reflect the real curves.
appropriately. For instance, at the beginning of the curves, $\alpha=1\ldots15$, in the middle $\alpha \approx 40$, and at the end $\alpha \approx 8$ provides a good approximation. It is clear that the characteristics highly depend on the temperature in the range of operating voltages, namely with small currents. Higher the temperature, less pronounced the non-linearity of the arrester. This means that increased temperature results in higher current with the same voltage that might result in thermal breakdown. With appropriate sizing, this problem can be eliminated. However, there are two major advantages of the ZnO resistors having high non-linearity. One of them is that owing to the low residual current, there is no need of a spark gap. The other is that the residual voltage is small. There are numerous other advantages of zinc-oxide surge arresters, which we do not describe here.

![E-J characteristics of arrester resistors](image)

**Fig. 6.116.** E-J characteristics of arrester resistors

The structure of zinc-oxide surge arresters is very simple, be it either in porcelain or in polymer (silicone rubber) housing. The latter one is shown in Fig. 6.117. The ZnO discs are situated close to each other in airtight silicone rubber housing. The endings are equipped with metal fittings for the connection of the unit to the line.

![ZnO overvoltage arrester with polymer housing](image)

**Fig. 6.117.** ZnO overvoltage arrester with polymer housing

### 7.2. LV overvoltage protecting devices

The metal-oxide surge arrester (varistor), the spark discharge tube filled with inert gas and the suppressor diode are low voltage overvoltage protecting devices.

#### 7.2.1. Metal oxide surge arrester (varistor)

The zinc-oxide (or metal oxide) surge arresters used in low voltage distribution networks, and in control circuits are called varistors. These are non-linear, voltage dependent resistors (VDR), the resistance of which decreases with increasing voltage $V$. In case of an overvoltage, they operate in very short time ($t \ll 25$ ns), and they can shunt large surge currents (max. 4000 A). The leakage current at operating voltage is small ($\leq 30$ μA).

![Varistor](image)

**Fig. 6.118.** Varistor
We have already discussed the properties and characteristics of ZnO resistors in section 6.7.1.2. Figure 6.118 shows a varistor. The VDR is situated in a disc-shaped epoxy housing between two electrodes. The diameter of the disc, depending on the type, is \( D = 7 \ldots 25 \text{ mm} \), and its thickness is \( v = 3 \ldots 8 \text{ mm} \).

1. If the size of the zinc-oxide grains is the same, then the varistor voltage is proportional to the thickness of the disc.

2. The permitted surge current is proportional to the cross section of the disc.

3. The diameter and the thickness together determine the loss and heat generated in the varistor.

### 7.2.2. Gas discharge tube (GDT)

The operation of the gas discharge tube (GDT) surge arrester is based on an electric discharge between two electrodes. Figure 6.119 shows its detailed structure, whereas Fig. 120 presents a tube design with connections. The picture indicates typical device sizes as well. The GDT contains a special, inert gas mixture between two electrodes, inside a sealed, cylindrical glass tube. The greater part of the gas mixture contains argon and neon. If the voltage across the electrodes surpasses the triggering voltage (depending on type 70 V ... 15 kV), then a breakdown occurs in the gas in a very short time, within some microseconds, and the device shorts the protected circuit. The voltage across the arc is low (10 ... 25 V), and owing to the small arc resistance (<0.1 \( \Omega \)), a high current flows through the device, which can withstand up to 60 kA current surges. If the arc quenches, the resistance of the GDT recovers to its original high value (\( \geq 10 \text{ G\( \Omega \)} \)). The surfaces of the electrodes are less than 1 mm apart, and they are covered with a special activating layer that improves the emission of the electrons. To be able to limit steep voltage surges (approx. 1 kV/\( \mu \text{s} \), GDTs has to operate fast. The inner surface of the insulator tube is coated by a layer that accelerates the ignition by distorting the electric field between the electrodes. Discharges occur randomly; therefore it is required from GDTs to operate within a tolerance if a slowly increasing DC voltage (approx. 100 V/s) is connected across its electrodes. Manufacturers can set these electrical parameters within a wide range, by adjusting the composition of the gas mixture, the electrode distance and the material of the activating and ignition accelerator layers.

![Fig. 6.119. Cross sectional view of a gas discharge tube](image)

![Fig. 6.120. Gas discharge tube](image)
7.2.3. Transient voltage suppression diode (TVS)

Short, but high amplitude voltage spikes can easily damage electronic equipment consisting integrated circuits. These voltage surges can occur during the switching of inductive or capacitive loads, due to electrostatic discharges or lightning strikes. Overvoltage protection of electronic devices can be effectively achieved by special Zener-diode arresters, also called as transient Zener absorbers (TransZorb diode). These diodes have a very short operating time (around 1 ns) and they are able to shunt current surges up to 400 Amps. A typical design of such diodes is represented by the suppression diode, which is metal enclosed, and has a high heat capacity (Fig. 6.121).

The voltage-current (U-I) characteristics of suppression diodes can be observed in Fig. 6.122. Overvoltage protective operation is determined by the reverse direction part of the characteristic curve. The characteristic voltage and current value pairs:

1. $V_R$ – maximum reverse standoff voltage, below which the diode does not conduct, and the corresponding small, leakage current $I_l (=1 \, \mu A)$,
2. $V_b$ – breakdown voltage, belonging to the breakdown current $I_b (=1 \, mA)$, and
3. $V_{R_{max}}$ – maximum reverse (zener) voltage, occurring with the highest permitted current peak $I_{pp}$ with standard 10/1000 $\mu$s current surge. This results in the maximum permitted peak-impulse power ($P_{pp} = U_{z_{max}} \cdot I_{pp}$).

In AC circuits, two diodes are connected in series in opposite direction. In this symmetrical case, when one of the diodes are triggered, and conduct in the reverse direction, the other diode will carry the current in forward direction. When forward current $I_F$ occurs, the forward voltage $U_F$ appears across the diode, determined by the characteristics (see Fig. 6.122).
7. fejezet - Properties and design of insulations

1. Operational stresses of insulations

The most important function of insulations is the reliable isolation of electrodes having different potential. Electric field is formed in insulation between electrodes and on the surface of these. The insulation can fulfill the requirement, as withstand to electrical stress, if its dielectric strength is enough high. It means that electric field formed by the voltage on electrode-arrangement does not cause breakdown in insulation or flashover its surface. At designing of insulations, the main requirement is that the insulation withstands breakdown and flashover stresses with high reliability and without failure.

Beside of electrical stress, the insulations have to satisfy other requirements. The insulations hold metallic components and electrodes (e.g. overhead powerline insulators, wound insulation) therefore they have important mounting function. Insulation has to be designed for static and dynamic mechanical stresses, as well.

Further important stress is the thermal stress. First, insulations are exposed to thermal stress from environment. Second, high voltage equipment generate heat during operation. At design of operational conditions of equipment, these stresses have to be taken into consideration.

Beyond thermal stress, other environmental stresses have effect on insulation. Such environmental effect is the oxygen from air, sun radiation, dust and gaseous pollution, humidity and different kind of biological effects (fungi, insects). These environmental effects are called environmental stresses.

To sum it up the objective of insulation technology is that examination of operational stresses and their effect on insulation. On the other hand, further aims of insulation technology are selection of insulating materials considering stresses in operation and sizing of insulation.

2. Fundamentals of insulation design

Insulating material can be endured by voltage stress which is lower than its dielectric strength. Therefore, at sizing of insulation, the maximum field strength is calculated. Nevertheless, in practice the voltage of electrodes are known, but they charges are unknown; hence the field distribution is determined from the voltage between electrodes.

From the point of view of insulation technology the most important parameter is field strength generated by voltage of electrodes. The utilization of insulating material is optimal, if the field distribution in the insulation is uniform in the whole volume of insulation. In this way, insulation having smallest volume can be given, theoretically. But, in practice, it cannot be done. Nevertheless, the aim of proper design is the optimal utilization of insulating material.

In practice the field intensity is not uniform. For example between two parallel plates the field intensity is significantly higher at the edges. The non-uniformity can be expressed by the ratio of the maximal and minimal field intensity, Emax/Emin. Distribution of field intensity is called strongly non-uniform if the previous ratio is higher than 10.

In case of some simple electrode arrangement (combinations of plane and cylindrical electrodes) the distribution of field intensity can be calculated by analytical methods. However in practice numerical field calculation is a better solution. Using such methods real 3D arrangements can be analysed. Usually such methods are available to calculate potential or field intensity values in the points of a predefined grid – usually by iteration. Different boundary conditions can be defined, like potential values of electrodes or charge values.

In the insulation engineering kV/cm is widely used as the unit of field intensity instead of V/m because of practical cases. Sometimes kV/mm or V/mm are used. The highest field intensity E\text{max} arising at the surface of one of the electrodes is determined by the shape and arrangement of electrodes and the applied voltage between them.
\[ E_{\text{max}} = f(U, \text{geometry}) \]

(7.1)

If \( E_{\text{max}} \) exceeds the dielectric strength of the insulating material, the insulation will be no longer suitable to separate electrically the different electrodes, a conductive plasma channel (electric discharge, practically electric arc) will be formed.

If the discharge appears inside the insulating material, the phenomenon is called breakdown. If the discharge appears along the boundary surface of two different insulating materials, the phenomenon is called flashover.

Fig. 7.1. Insulation a) breakdown, b) flashover és c) partial discharges

In case of strongly non-uniform electric field (eg. in case of parallel wires of transmission lines or – in general – near a sharp edge or a peak of an electrode) the field intensity exceeds the dielectric strength only near to the electrodes, outside of this region the field intensity remains below the critical level. In such a case (especially in case of gaseous or liquid insulations) electric arc between the electrodes cannot be formed, the discharge is limited to the strongly non-uniform part. This phenomenon is called partial discharge.

There are different problems connecting to the partial discharges. First one is the energy loss caused by them, another one is the emission of radio-frequency, but the most difficult problem is that inner discharges formed in air inclusions and surface discharges destroy the structure of the insulation. Due to such damages a total breakdown can appear.
8. fejezet - Diagnostics of insulations

As it was presented before, the most important parameter of the insulation is the dielectric strength. Its reason is the following. The main task of the insulation is the electric separation of electrodes at different potentials [28, 29]. To fulfil requirements connected to this task it is important to apply insulations with appropriate dielectric strength.

However, dielectric strength is not a constant value; it is continuously decreases during the lifetime of the insulation due to the operational stresses. After a certain time dielectric strength reach a critical limit, when the risk of breakdown is so high, that requirements of safe operation cannot be fulfilled. In other words, the safety factor of the insulation decreases to a critical level.

Phenomenon resulting decreasing dielectric strength due to non-reversal degradation processes is called the ageing of the insulation [30]. These chemical, physical degradation processes are initiated by the operational stresses of the insulation.

Most important chemical degradation processes are:

1. oxidation: infiltration of oxygen molecules into the molecular structure

2. depolimerisation: breaking of giant molecules of the insulation

3. polimerisation: transformation of the molecules of insulation into molecules with higher molar mass

Different insulations have different ageing processes. These processes are characteristic for the insulation, thus the ageing process of oil-paper insulation, PVC or PE insulation are different.

Increasing humidity in the insulation is mainly a physical process. In case of insulation operating in a wet environment (e.g. in soil) water molecules diffusing into the insulation make dissociation processes more intensive, thus they influence the electric properties (e.g. insulation resistance) directly and they can accelerate the ageing process due to their catalysing effect. Wetting can result in chemical change as well, when water molecules are integrated into the molecular structure.

Slow diffusion process on the surface of certain chemical components (e.g. plasticiser) in case of plastic insulators is also a physical process. Flexibility of insulation decreases the material becomes rigid [Wypych 2004].

Characteristics of ageing processes depend on the properties of specific insulating materials and the types of stresses.

1. Fundamentals of examination of insulations

As it was written before, ageing of insulating is caused by electric, mechanical and other stresses (e.g. chemical effects from the environment, humidity and oxygen of air, UV and radio active radiations, etc.). These stresses initiate different physical and chemical processes that change the molecular structure of the insulation. Such structural changes decrease the dielectric strength and make other properties worse causing degradation, and the ageing of insulation.

Direct measurement of the decrease in dielectric strength is not possible without the damage of the insulation: unfortunately this is a destructive test method, thus the insulation can no longer act as an electrical separation between different potentials, so its further operation is not possible. Situation is similar to the previous one from the point of the mechanical properties as well.

During the recent years several electrical (and not electrical) test methods were developed that are non-destructive ones and suitable for the determination of the condition of the insulation. Such methods can describe the intensity and state of different degradation processes (like thermal ageing, wetting) without the destruction or significant overload of the insulation. The common expression for these non-destructive test methods is insulation diagnostic methods.
Theoretical background of traditional diagnostic methods is the following. Chemical and physical degradation processes change the molecular structure, thus the physical and electrical properties as well. For example a degradation process can decrease the dielectric strength through the “degradation >> change of molecular structure >> dielectric strength” relationship. (See Fig. 8.1).

Fortunately the change in the molecular structure influences not only the dielectric strength, but also the fundamental dielectric processes, like conduction and polarisation. These processes can be examined using non-destructive tests. Based on the test results of the examination of polarisation and conduction processes it is possible to estimate the degree and intensity of the degradation process.

The way of analysis is the following. Based on the diagnostic tests determination of the change of dielectric processes >> estimation of the change of molecular structure >> estimation of the change of dielectric strength. Unfortunately relationship between dielectric strength and dielectric properties determined based on diagnostic test is not a simple one, thus practical limits have to be defined based on several measurements and a long experience. Reliability can be increased with systematic application of diagnostic tests (e.g. year to year), because the “speed” of degradation can be determined.

2. Methods of insulation diagnostic tests

Processes of electric conduction and polarisation can be examined by the measurement of dielectric properties of the insulation. Test methods can be classified based on the measured physical property.

One possible classification is the following: some test methods examine the dielectric properties in the time domain, other ones in the frequency domain [32-34]. Another possible classification is this: which methods are able to determine properties of conduction and which ones are suitable for the determination of the properties of polarisation, how can the two processes be separated. Such classification can be seen in [35].

Fundamentals of different DC diagnostic methods can be easily followed according to Fig. 7.2, where the time function of the measured parameters can be seen.
Fig. 7.2. Dielectric measurements in time domain [34]

Notation of parameters is the following.

Charging time: $t_{ch}$; discharging time: $t_{dp}$; self- (independent) discharging time: $t_{idp}$; time between voltage zero and peak of return voltage $t_{max}$; recording time of return voltage ($t_{rvp}$).

Further parameters denoted in the figure:

1. Time function of polarising and depolarising currents ($I_{p}(t)$, $I_{dp}(t)$) and their peak values ($I_{pmax}$, $I_{dpmax}$)
2. Times functions of charging voltage ($U_{ch}(t)$), discharging voltage ($U_{d}(t)$) return voltage ($U_{r}(t)$); peak value of return voltage ($U_{rmax}$),
3. Initial steepness of discharging and return voltage ($S_d$ and $S_r$).

Taking into consideration the aforesaid parameters the most widely used evaluation methods for DC measurements are the following ones:

1. Measurement of charging and discharging current:
   1. Measurement of leakage current test
   2. Measurement of relaxation current (IRC),
   3. Time domain spectroscopy (TDS).
2. Measurement of discharging and return voltage:
   5. Method of total voltage response (VR),

In case of AC tests the most widely used measurements are the following:

1. Loss factor at industrial frequency (50/60 Hz)
2. Loss factor at low frequencies
3. Loss factor measured by oscillating wave
4. Loss factor as a function of frequency (FDS).

Beyond the previous tests another widely used test method is the measurement of parameters of partial discharges formed inside the insulation or on the boundary surface of different insulating materials.

The most important difference between dielectric and partial discharge measurements is their content of information. Measurement of dielectric properties are based on the examination of dielectric and polarisation processes to estimate the actual condition of the insulation. Measurements of partial discharges give information about the insulator and not the insulating material, because the results of these measurements are influenced by the geometry, the environment of the insulator, the faults in the insulator, etc.

Furthermore, partial discharges are formed at local faults, thus it is not possible to estimate the overall condition and ageing of the insulation.

Thus, measurement of the parameters of partial discharges is very suitable for the determination of local faults. Such measurement is the test with oscillating wave (OWTS) that is applied for high voltage cable lines nowadays [36]. Selectivity of the method is much better when the partial discharges are measured in an acoustic way. In this case the adequate position of faults (like the ones made during the installation of the cable) can be determined with high accuracy.

Significant advantage of the partial discharge measurement, that in most cases it is suitable for on-line tests.
9. fejezet - Examples

1. Example

A DC electromagnet pulls a contactor’s contacts if the current in its coil reaches 2.3 A. The rated voltage of the coil is 24 V<sub>dc</sub>, and its operating current is 2.9 A.

1. How much time does the electromagnet need to pull-in after turning on the circuit, if the coil’s inductance is 3.98 H?

2. How can this starting time be decreased to 1/5 of its original value, if the coil cannot be changed?

2. Example

I=12 kA steady-state fault current flows in a low voltage circuit supplied by V=230 V. The power factor of the circuit is cos<sub>θ</sub>=0.4, the frequency is f=50 Hz.

Determine the resistance (R) and inductance (L) of the circuit!

3. Example

I<sub>max</sub>=50 kA steady-state fault current was measured in a circuit with cos<sub>θ</sub>=0.2. How much is the momentary value of the current at t=10 ms measured from the occurrence of the current, if

1. the fault current started at the moment of voltage zero?

2. the fault current begun at the steady-state current zero?

4. Example

How much permanent load current can be allowed, and how much is the temperature time constant, if the current flows in an infinite long copper bus bar with a cross sectional area of 100’10 mm, and the temperature rise allowed is τ<sub>max</sub>=60 K? (ρ<sub>Cu</sub>=2.27·10<sup>-8</sup> Ωm, c<sub>v</sub>=3.38·10<sup>6</sup> Ws/m<sup>3</sup>K) Two arrangements are to be considered: the bus-bar is laid on its thinner, and on its wider edge. The film coefficient in case of smooth vertical surface and free convection is α = 2.55·<sup>1/3</sup>τ<sub>max</sub> [W/m<sup>2</sup>K]. If the surface is horizontal, it is half of the vertical case.

5. Example

The minimum interrupting current of an MCB is I<sub>s</sub>=14.5 A. The temperature of the bimetallic strip in the MCB had been equal with the ambient temperature, when a current of I<sub>r</sub>=24 A started flowing in the circuit. After t<sub>r</sub>=69.5 s, the MCB interrupted the current.

Now, an ohmic load of P<sub>0</sub>=1300 W has been connected to the circuit for a long time. How much will be the interruption time, if we turn on an additional electric motor with P=2.0 kW and cos<sub>θ</sub>=0.8? The supply voltage is V=230 V.

6. Example

How much is the maximum force between two parallel, filamentary conductor pieces, having equal length of l=3 m at a distance of R=10 cm (see figure below)? A usual current peak factor can be considered, and the rms quasi steady-state fault current is I<sub>st</sub>=12 kA.
7. Example

The constriction resistance between two contacts has been measured as function of the pressing force. Two corresponding points from the measurement:

\[ F = 15.8 \text{ N}, \quad R = 6.01 \times 10^{-5} \Omega \quad \text{and} \quad F = 8.0 \text{ N}, \quad R = 7.54 \times 10^{-5} \Omega. \]

With a current of \( I = 160 \text{ A} \), how much shall be the pressing force to reach the softening temperature (\( \vartheta_s = 190 ^\circ \text{C} \)) of the contact material, if a temperature of \( \vartheta_0 = 77 ^\circ \text{C} \) was measured far from the constriction, and \( L = 2.5 \times 10^4 \) (V/K)?

8. Example

Ideal interruption of a CB terminal fault in a circuit having serial and parallel damping:

\[ \cos \varphi = 0.1; \quad C = 1 \mu \text{F}; \quad R = 200 \text{ m}\Omega; \quad r = 200 \Omega; \]

1. How much is the voltage peak factor \( k_{\text{peak}} \)?
2. How much should \( r \) be, in order to get an aperiodic transient recovery voltage?

9. Example

\( V_{\text{rms}} = 70 \text{ kV} \) generates \( I_{\text{rms}} = 50 \text{ kA} \) short circuit current in the circuit (f=50 Hz). How much is the average steepness of the TRV, if the stray capacitance is \( C = 0.15799 \mu \text{F} \)? Determine the time function of the TRV.

10. Example

A fast operating CB interrupted the prospective fault current having the highest transient component in a circuit without parallel and with serial damping. The interruption occurred in

1. the first,
2. second current zero.

Measurements provided the damping factor of the TRV’s oscillating component: \( \delta = 17.86 \text{ 1/s} \). How much is the rate of the two TRVs’ steady-state components belonging to the moments of current interruption (\( V_{R1}/V_{R2} \))? 

11. Example

A CB terminal fault occurred in an HV circuit having a power factor of \( \cos \varphi = 0.1 \) in two different cases:

1. at the moment of voltage zero,
2. at the moment of steady-state current zero.

The fast operating CB interrupted both of the currents exactly at the first current zeros after fault occurrence. How much is the rate of the two TRVs’ steady-state components belonging to the moments of current interruption? \( \frac{V_{n1}}{V_{n2}} \)

**12. Example**

The following voltage and serial resistance values provided the same point of a steady-state arc characteristic:

\[
\begin{align*}
U_{n1} &= 230 \text{ V} \quad \text{and} \quad R_1 = 10 \text{ Ω} \\
U_{n2} &= 120 \text{ V} \quad \text{and} \quad R_2 = 4 \text{ Ω}.
\end{align*}
\]

How much is the conductivity of the arc at this point?

**13. Example**

A circuit breaker successfully cleared a terminal fault current of \( I_{\text{rms}} = 66.67 \text{ kA} \) in a circuit supplied by a peak voltage of \( U_{\text{peak}} = 100 \text{ kV} \): the TRV with \( f_{01} = 5 \text{ kHz} \) frequency did not re-ignite the arc. However, in case of a short line fault occurred on an overhead transmission line with \( Z = 450 \text{ Ω} \) surge impedance, the interruption was unsuccessful, the arc between the CB contacts was dielectrically re-struck after \( t_{\text{rs}} = 8 \mu\text{s} \) from the current zero. The short circuit current in this latter case was \( I_{\text{rms}} = 40 \text{ kA} \).

How much is the arc time constant, and how far did the fault occur from the CB terminals, if the restrike voltage at the moment of current zero was \( U_{\text{ns}} = 30 \text{ kV} \).

(The resistances in the circuit and the time variation of the steady state component of the recovery voltage during the transients can be neglected.)

**14. Example**

The in-rush current during the switch-on of an idle, three-phase transformer with rated power of \( S = 20 \text{ MVA} \), and rated voltage of \( V_r = 35 \text{ kV} \) varied between \((3...7) \times I_n \). In all the cases, the currents started exactly at voltage zeros.

1. How much were the smallest and largest in-rush currents in amps?

2. How much is the initial steepness \( m \) of the transformer’s \( \Psi(i)_\text{init} \) function, if its initial section is approximated by linear function?

During the calculation, a single-phase model can be used and the serial damping can be neglected.

**15. Example**

How much is the possible largest in-rush current \( I_{\text{minit}} \) during the switch-on of a no-load three-phase transformer with rated voltage of \( V_n = 20 \text{ kV} \), if the if the initial section of \( \Psi(i)_\text{init} \) can be approximated by linear function with a steepness of \( m = 0.003 \text{ Vs/A} \)?

**16. Example**

The average steepness of the TRV in a loss-free circuit, where a short-circuit current has been flowing, is \( m_{av}=3\text{ kV/ms} \). The natural frequency of the circuit is \( \omega_0 = 40000 \text{ rad/s} \). How much can be the possibly largest instantaneous value of the current, if the serial inductance of the circuit is \( L = 4 \text{ mH} \)? The frequency of the exciting voltage is \( f = 50 \text{ Hz} \).

**17. Example**
At a \( t = 5 \) ms after the beginning of a fault current, a negative current was measured. It was 60 % of the steady-state peak current \( (i(t_1)/I_{m} = 0.6) \). The frequency is \( f = 50 \) Hz.

How much is the power factor \( (\cos \varphi) \) of the circuit, and the switch-on angle \( (\varphi) \), if the possible largest DC component occurred during the fault?

### 18. Example

The armature of a DC electromagnet starts moving, when the current in its coil reaches \( I_{\text{start}} = 3.2 \) A. The rated voltage of the coil is \( V_o = 120 \) V. The inductance of the coil is \( L = 7.5 \) H. The steady-state current in the coil is \( I_{\text{start}} = 8.0 \) A, and its temperature is \( \vartheta = 20 \) °C. The thermal coefficient of the coil material is \( \alpha' = 4 \times 10^{-3} 1/\text{°C} \) at \( \vartheta = 20 \) °C.

After turning on the supply voltage, how much time \( (t_{\text{start}}) \) elapses before the armature starts to move, if the temperature of the coil is:

1) \( \vartheta_1 = 20 \) °C,
2) \( \vartheta_2 = 90 \) °C?

### 19. Example

How much is the steady-state temperature \( (\vartheta_{\text{st}}) \) of an infinite long, rectangular busbar laid on its thinner side if a current of \( I = 2500 \) A flows through it? The cross sectional size of the busbar is \( 80 \times 20 \) mm²

Further data: \( \rho = 2 \times 10^{-8} \Omega \text{m} \), \( \vartheta_{\text{amb}} = 20 \) °C, \( \alpha' = 4 \times 10^{-3} 1/\text{°C} \) and \( \alpha = 2.55 \times \sqrt[3]{\vartheta} \left[ \frac{W}{m^2 \text{K}} \right] \) for smooth, vertical surface with natural convection.

### 20. Example

An MCB interrupts the circuit after \( t_{\text{r}} = 120 \) s, if a current of \( I_{\text{r}} = 35 \) A flows through it. The smallest disconnection current of the MCB is \( I_{h} = 22 \) A. How much is the disconnection time \( (t_{\text{r}}) \), if the MCB has been loaded by a current of \( I_{\text{r}} = 10 \) A for a long time, and we add another load to the circuit, which takes \( I = 45 \) A?

### 21. Example

The highest force acted between two parallel, 1 m long conductors in a single-phase solely inductive circuit was \( F_{12} = 4000 \) N. How much was the rms steady-state current, if the distance between the parallel conductors was \( R = 150 \) mm?

### 22. Example

How much is the possible largest fault current peak factor in a circuit with a power factor of \( \cos \varphi = 0.15 \)? The frequency is \( f = 50 \) Hz.

### 23. Example

The steady-state current in a DC L-R circuit is \( I_{\varphi} = 100 \) A. The supply voltage is \( V_{\varphi} = 120 \) V. At \( t = 5 \) ms after closing the circuit, the momentary value of the current is 50 % of the steady-state value. Determine the circuit’s parameters \( R \) and \( L \).

### 24. Example

During the switch-on of a capacitive load we measured the following voltage at the capacitor and current in the circuit at \( t = 20 \) ms: \( V_{\varphi} = 20 \) V, \( I_{\varphi} = 0.1 \) A. The supply voltage is 24 V DC. Determine the circuit parameters \( C, R \) and the time constant \( r \) of the circuit.
25. Example

A terminal fault current occurred in a DC circuit, and it reached \( I_1 = 2000 \text{ A} \) in \( t_1 = 2 \text{ ms} \) and \( I_{\text{open}} = 4000 \text{ A} \) in \( t = 5 \text{ ms} \) after switch on. The supply voltage was \( V_0 = 110 \text{ V} \). The current was interrupted by a circuit breaker, its contacts were separated at the moment of \( I_{\text{open}} \), and the time function of the arc voltage was \( U_{\text{arc}} = mt \), where \( m = 100 \text{kV/us} \).

a) How much was the total fault clearing time?

b) A fault current occurred in the same circuit at the same location, but now the protective device was a fuse, with a fuse element of \( A = 0.5 \text{ mm}^2 \) cross sectional area. How much was the total fault clearing time, if a constant voltage of \( V_{\text{arc}} = 200 \text{ V} \) was measured across the fuse during arcing?

Initial temperature of fuse element: \( \theta_v = 30 \text{ °C} \)

Melting temperature of copper: \( \theta_{\text{melt}} = 1083 \text{ °C} \)

Resistivity of copper at \( \theta_0 = 20 \text{ °C} \): \( \rho_{\theta_0} = 1.75 \cdot 10^{-8} \Omega \text{m} \)

Specific heat of copper at \( \theta_0 = 20 \text{ °C} \): \( c_{\theta_0} = 3.4 \cdot 10^6 \text{ Ws/m}^3\text{°C} \)

Temperature factor of copper related to \( \theta_0 = 20 \text{ °C} \): \( \alpha_{\theta_0} = 4 \cdot 10^{-3} \text{ /°C} \)

26. Example

In the following example, we demonstrate a practical case of contactor selection. The initial data we know:

1. A squirrel cage asynchronous motor is to be switched with dynamic breaking;
2. The rated voltage of the motor: \( V_r = 400 \text{ V} \);
3. The rated power of the motor: \( P_r = 25 \text{ kW} \);
4. The rated current of the motor: \( I_r = 50 \text{ A} \);
5. The switching cycles per hours: \( 360 \text{ c/h} \);
6. Expected lifetime of the contactor: 0.3 year.

Solution:

1. The utilization category of the contactor: AC-4.

2. From the diagram of Fig. 6.104, the correction factor in utilization category AC-4 and with 360 switching cycles per hour is \( k = 80 \% \).

3. The corrected rated current of the motor from formula (6-12):

\[
I_{\text{rcor}} = \frac{10050}{80} = 125 \text{ A}
\]

1. The expected lifetime of the contactor, assuming 50 weeks a year and 40 hours a week:

\( D_{\text{exp}} = 0.3 \text{ year} \cdot 50 \text{ week/year} \cdot 40 \text{ hour/week} \cdot 360 \text{ sc/h} = 2.16 \cdot 10^5 \text{ sc} \).

1. The switch-off current of the motor owing to the utilization category AC-4:

\( I_{\text{of}} = 6 \cdot I_{\text{rcor}} = 6 \cdot 125 = 750 \text{ A} \).

1. Considering that \( D_{\text{exp}} = 2.16 \cdot 10^5 \text{ sc} \) and \( I_{\text{of}} = 375 \text{ A} \), from the diagram in Fig. 6.103, we have to choose the largest of the first contactor type denoted by 132. The maximum switching power with this contactor would be \( P_{\text{max}} = 132 \text{ kW} \) in utilization category AC-3. It is also clear from the diagram, that the real lifetime of the chosen contactor is \( D_{\text{real}} = 2.55 \cdot 10^5 \text{ sc} \).
2. If we operated the motor with the selected contactor in category Ac-3, then, according to Fig. 5.126 – and because of $I_{\text{nom}} = I_{\text{corr}} = I_{\text{off}} = 50$ A – the contactor durability would be $D_{\text{real}} = 6.8 \times 10^6$ sc.

3. If we operated the motor with the selected contactor in mixed mode, 90 % in category AC-3 and 10 % in category AC-4, then – as the relations $D_{1} = D_{\text{real}} = 6.8 \times 10^6$ sc and $D_{2} = D_{\text{real}} = 2.55 \times 10^5$ sc are valid – according to formula (6-13), the lifetime of the contactor would be:

$$D_m = \frac{6.8 \times 10^6}{1.9 \times 10^6 \left( \frac{6.81 \times 10^6}{24610^3} \right)^{-1}} = 1.9 \times 10^5 \text{ sc.}$$

The merely 10 % heavy duty reduced the durability almost to its quarter, compared to a sole AC-3 operation.
Bibliography


Koller, L.. „Az áramvezető sínekről". pp. 91-96. *Elektrotechnika*. 2000. 93. 3. sz..


Madarász, Gy.. „Nagyfeszültségű megszakítók fejlődési tendenciái”.* Elektrotechnika*. 1996. 89. évf.. 3. sz..

Madarász, Gy.. „Kis induktív áramok kapcsolásakor keletkező túlfeszültség-igénybevételek II.”. *Elektrotechnika*. 1995. 88. évf.. 1. sz..

Madarász, Gy.. „Kis induktív áramok kapcsolásakor keletkező túlfeszültség-igénybevételek I.”. *Elektrotechnika*. 1994. 87. évf.. 11. sz..


