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Medium-voltage fuses

Technical guide

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Content

1. Introduction

ABB, meeting the needs of the medium-voltage fuse-link users, decided to provide a guide with basic information to facilitate understanding of the main aspects related to the first protection device ever used in the power industry. This manual is written in such a way that its content can be useful for people who use high-voltage fuse-links in everyday professional practice.

At the beginning, the international standards covering the subject of high-voltage fuse-links are reviewed. As standardisation documents constitute a set of best engineering practices, their knowledge and compliance with them are well perceived in the industry.

The next section contains classification of high-voltage fuse-links for their design and switching parameters. Although manufacturers offer high diversity of fuse-link designs with different construction features, their correct classification should not be a problem.

The fourth chapter is fully dedicated to the current-limiting fuse-links and is divided into several parts. It describes the construction of the fuse-link and its electrical parameters. It also explains the activation and purpose of fuse-link indicator. The section also describes the effect of the short-circuit current limitation and provides guidelines for the proper selection of fuses to protect the equipment in selected applications.

Finally, some advices on the basic rules of fuse-link handling are given. The ABB company hopes that reading this handbook will be a valuable complement to your professional experience.

2. Standards

High-voltage fuses like other devices are subject to standardization processes. Standardization is understood as the set of best practices provided in the individual documents. Although the application of standards is voluntary, practice shows that compliance with them is well perceived and even required by customers.
In the standardisation area, there are two main organizations taking the issue of standardization: the European IEC (International Electrotechnical Commission) and American IEEE (Institute of Electrical and Electronics Engineers). Both the organizations actively participate in the standardization of high-voltage fuses.
The work area of the European IEC Standardization Committee covers several standards for high-voltage fuse-links. The basic standard defining the high-voltage current-limiting fuses is the IEC 60282-1 (High-voltage fuse – Part 1: Current-limiting fuses) [2].
The standard describes the technical parameters that must be met. Even though this standard is very extensive, it does not define the time-current characteristics for individual types of fuse-links. The shapes of characteristics of individual fuses are indirectly included in other standards, e.g. in IEC/TR 62655 (Tutorial and application guide for high-voltage fuses.) [4].
Fuses designed for protection of motor circuits are described in the standard IEC 60644 (Specification for high-voltage fuse-links for motor circuit applications) [1]. The fuse-link designed to protect the AC motor circuits shall meet the conditions described in IEC 60281-1 [2], and shall have the capability to withstand repetitive current surges related to the starting of the motor defined in IEC 60644.
The capacitor bank protection fuse-links are described in IEC 60549 (High-voltage fuses for the external protection of shunt capacitors) [3]. Also in this case the fuse should meet the requirements described in the general standard IEC 60282-1 [2], with additional tests resulting from this standard. The summary of the analyzed standardization documents is shown in diagram 2.1.

Fig. 2.1.

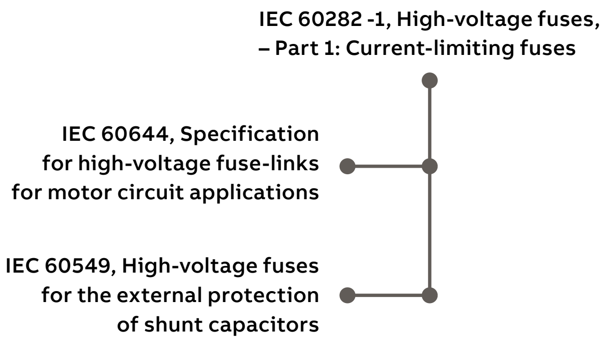

Fig. 2.1.
European standards covering the topic of high-voltage fuses.

Fig. 2.2.

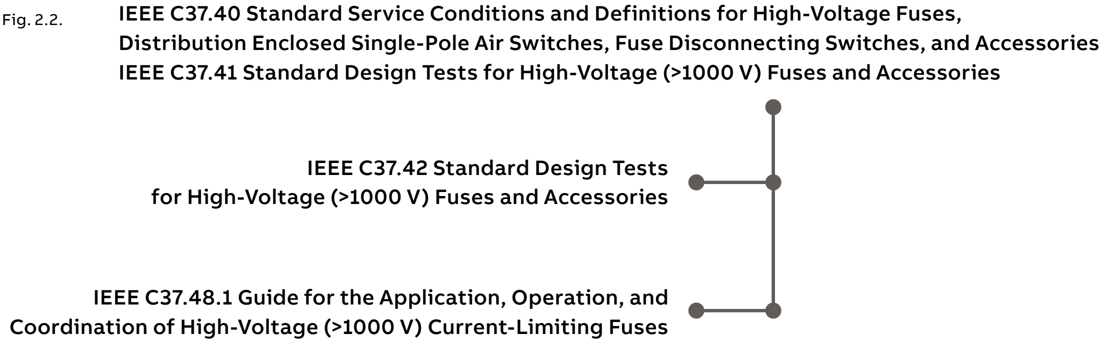

Fig. 2.2.
US standards covering the topic of high-voltage fuses.

3. Classification

The high-voltage fuses can be divided into the expulsion fuses and the short-circuit current-limiting fuse-links. This division is due to the design of the fuses and their principle of operation. The expulsion fuse-links break the current by exhausting gases out of the fuse area, whereas the current-limiting fuses use the effect of fuse-element evaporation in loose materials. As the expulsion fuses do not have the ability to limit the short-circuit currents, their parameters are limited. The current-limiting fuse-links are through their structure capable of significantly reducing the level of short-circuit currents, which makes their parameters relatively high compared to the short-circuit power that is available in the power grid. The fuse-links manufactured by ABB are able to break the short-circuit current up to 63 kA rms for rated voltages from 3.6 kV to 24 kV, and 40 kA for rated voltage from 36 kV to 40.5 kV. Higher parameters e.g. short-circuit currents, are technically feasible, but difficult to type test as they exceed the available short-circuit power of testing laboratories.
The further division of the current-limiting fuse-links results from the minimum currents which the fuse is able to interrupt. There are back-up fuses, general-purpose fuses and full-range fuses. This division is described in detail in the high-voltage current-limiting standard IEC 60282-1 [2]. The range of high-voltage fuses operation depending on the class is shown in Fig. 3.1.

Fig. 3.1.

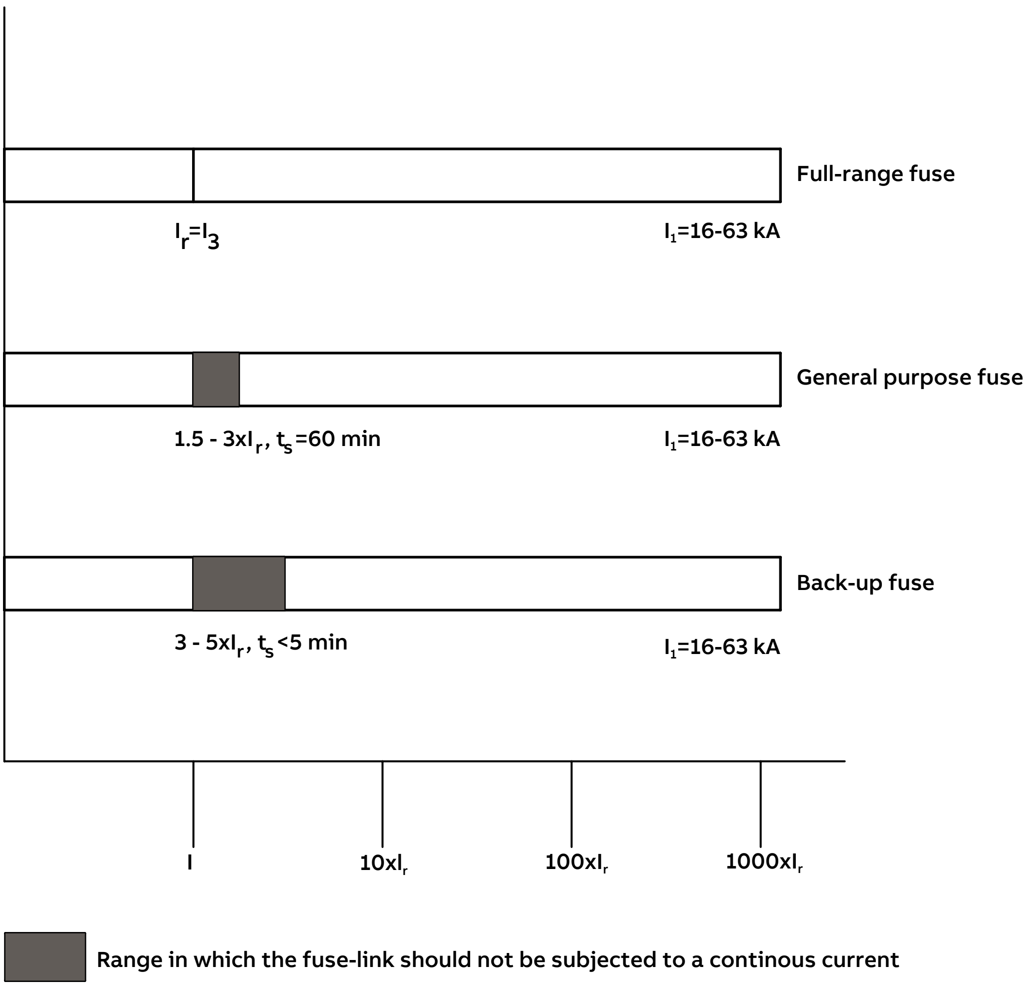

Fig. 3.1.
Operating ranges of fuse-links depending on class.

I_r – rated current
I_3 – minimum breaking current
I_1 – breaking capacity
t_s – pre-arcing time

The current-limiting back-up fuse-links are characterized by the minimum breaking current of approximately four times the rated current value. For example, a fuse-link for the rated voltage of 24 kV and the rated current of 25 A has a minimum breaking capacity of 100 A, and below this value there is an uncertain breaking area where the breaking capability is limited and very often depends on circuit operating conditions. This type of fuse-links is typically used in power industry where the circuit allows the occurrence of overload currents below the declared value of minimum breaking current, and the breaking function is carried out by another device in proper coordination, e.g. switch-disconnector.
The interoperation of the fuse and the switch-disconnector is further addressed in the section 4.6.

The general-purpose fuse-links are capable of breaking currents that will melt the fuse-link during one hour, which usually means that the rated current is 1.5 to 3 times the rated current. Such type of fuses are similar to back-up fuses in their design, with the difference that the number of fuse-elements connected in parallel is greater, which also increases the diameter of the fuses.
The last group of the current-limiting fuses are the full-range fuse-links that are capable of breaking any current which can interrupt the fuse circuit; the referred standard specifies that pre-arcing time must be longer than one hour. Obtaining such parameters typically requires serial integration of a back-up fuse-link and an expulsion fuse-link in one device.

4. Current-limiting fuse-links

This chapter focuses on the description of high-voltage current-limiting fuse-links. A high-voltage expulsion fuses are the subject of a separate publication and also exist in ABB MV fuses portfolio, used mainly as a protection of capacitor banks, dedicated for ANSI market.

4.1. High-voltage fuse construction

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Fig. 4.1.
High-voltage fuse-link and its characteristic components.
A – striker or indicator
B – end cap (fuse-link contact)
C – body
D – star core (former)
E – granular filler
F – fuse-element
G – low temperature overlay("M effect")

The IEC standard defines a fuse as a complete device for insertion into a circuit, which consists of a fuse-base and a fuse-link. In practice, however, the terms "fuse" and "fuse-link" are used interchangeably and usually refer to a replaceable protective device - fuse-link. The currently manufactured by ABB fuse-links cover the nominal voltage from 3 kV to 40.5 kV and the nominal current from 0.5 A to 315 A. Obtaining higher rated currents is possible by parallel connection of fuse-links. The fuse dimensions depend mainly on its rated parameters. The length parameter is correlated to the rated voltage level at which the fuse is operated. The fuse diameter is determined by the fuse rated current, therefore the higher the rated current the larger the fuse diameter. The main components of the fuse is the insulating body, fuse-element, fittings and extinguishing material. The construction of the HV current-limiting fuse-link is shown in Fig. 4.1.

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Fig. 4.1.

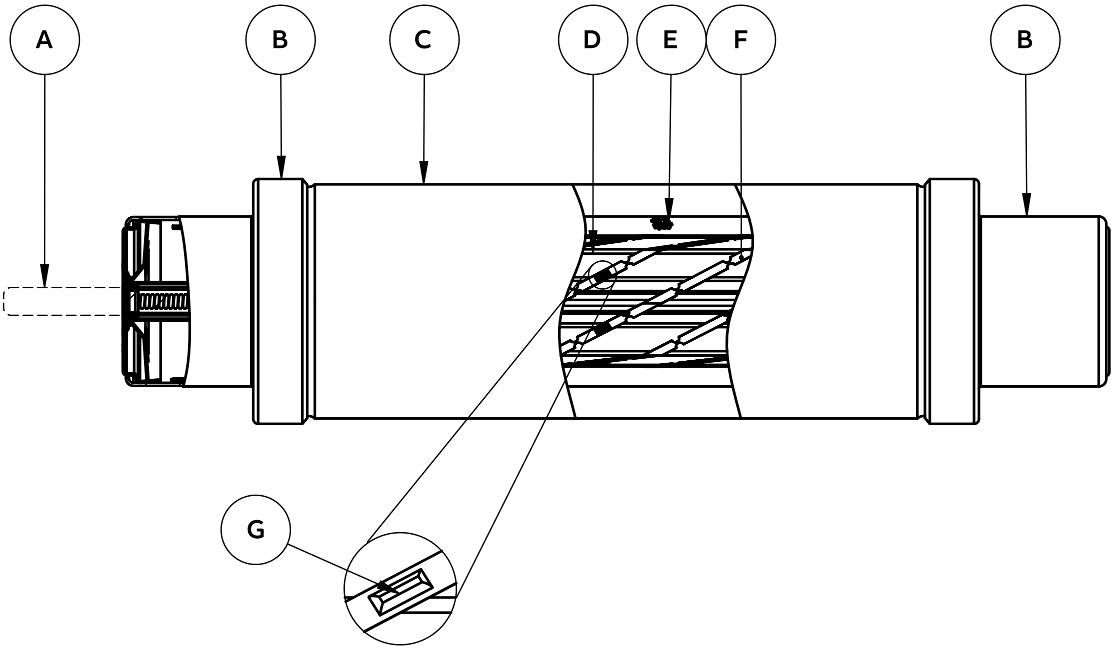
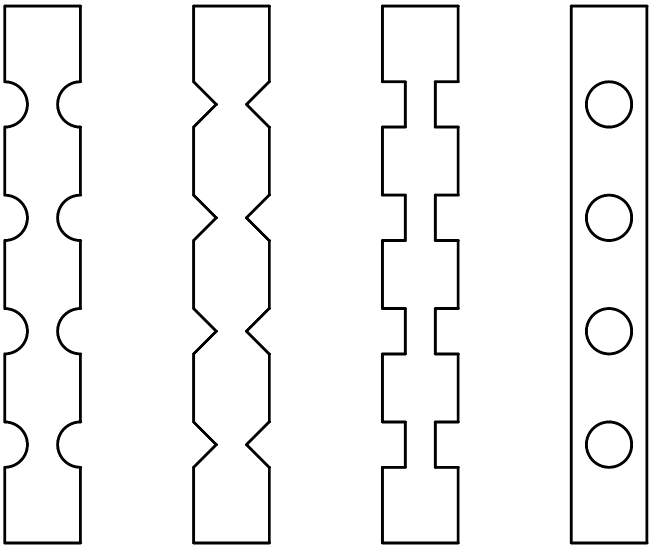


Fig. 4.2.
Typical shapes of narrowings used in high-voltage fuses.

The breaking of the current is accompanied by energy surge in the form of pressure and heat, therefore the structure of the body should be strong enough and able to prevent blowing the decomposition products to the outside. The fuse-link bodies are usually made of electrotechnical porcelain. The main part of the fuse is the fuse-element, whose shape determines the time-current characteristic. The main material used for the construction of the fuse-element in high-voltage fuses is high purity silver. Due to the high temperatures of the fuse-links observed during operation at rated conditions, the use of a material like copper may result in an unjustified breaking of the fuse-element as a result of oxidation processes. High-voltage fuses using copper may also change their time-current characteristics over time, as the actual cross-section of the fuse-element is reduced due to oxidation processes.

In the case of the relatively low current fuses (up to 5 A), the fuse-element resembles a wire, whereas for higher rated currents has a strip shape. Designing the shape of the time-current characteristic for the fuse-links with wire is usually reduced to selecting the cross section of the fuse-element therefore their characteristics in the upper area are similar to a vertical line. In the case of strip-shaped fuse-element, the shape of the characteristics can be modified by making cutouts in the production process that narrow the strip. The shape of narrowings and their number have effect on the characteristics throughout the entire operating range of the fuse. Individual producers use specific shapes of narrowings which are often subject to patent protection. Typical shapes of narrowings in the strip-shaped fuse-element are shown in Fig. 4.2.

Fig. 4.2.



The thermographic image showing the strip fuse-element used in high-voltage fuses in the steady state condition is presented in Fig. 4.3. The temperatures correspond to the current load of 50% of the rated current, i.e. the typical conditions while protecting the transformer against the effects of short-circuit.

Fig. 4.3.

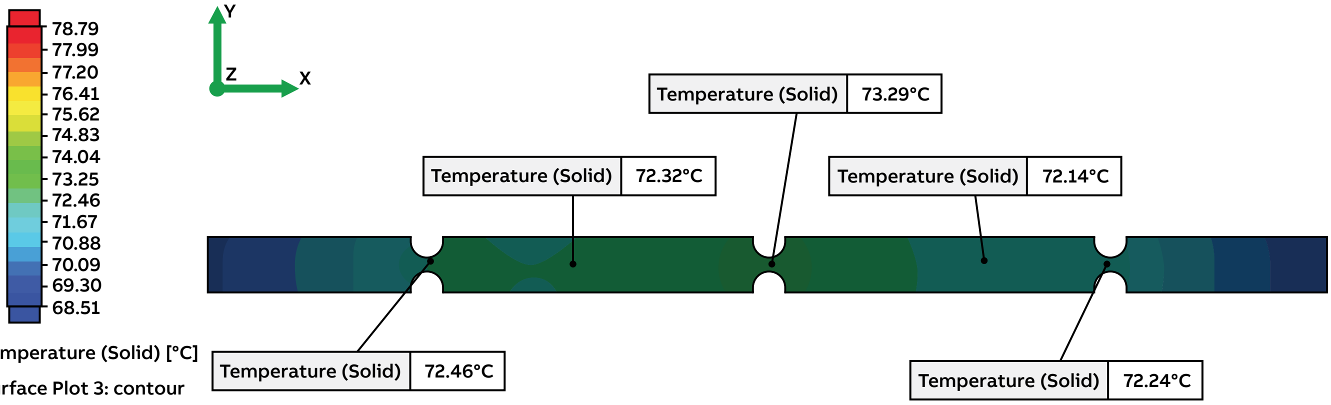


Fig. 4.3.
Strip-shaped fuse-element used in high-voltage fuses.

One of the structural measures used to shape the time-current characteristics of the fuse is the so-called overload point. A metallurgical effect (so-called the “M-effect”) is used to create an overload point, and it is made by placing a short metal piece of low melting temperature onto the fuse-element. The metallurgical effect was first described by Professor Metcalf in the thirties of the 20. century. It consists of a phenomenon of melting the metals fusible at higher temperatures (copper, silver) by means of materials melting at lower temperatures (e.g. tin, lead). A fuse-element made of silver with a fitted low melting metal piece (soldering) is melted at the values of currents which would not cause melting of the fuse-element without an overload point. This is due to the fact that during warm-up of a fuse-element with the overload point, the metal from which the overload point is made begins to melt and dissolve the metal in contact with it. By using the overload point, the temperature of the fuse body is reduced, and additionally, in overload states, it can be electric arc initiated at the metal contact point, which is beneficial for interrupting process.

The length of the fuse is typically shorter than the length of the fuse-element therefore the fuse-elements are wound onto a core. The X-ray image showing the fuse with several fusible strips is presented in Fig. 4.4. The monitoring of the production process using industrial X-ray devices effectively improves the process of quality inspection of the manufactured fuses.

Fig. 4.4.

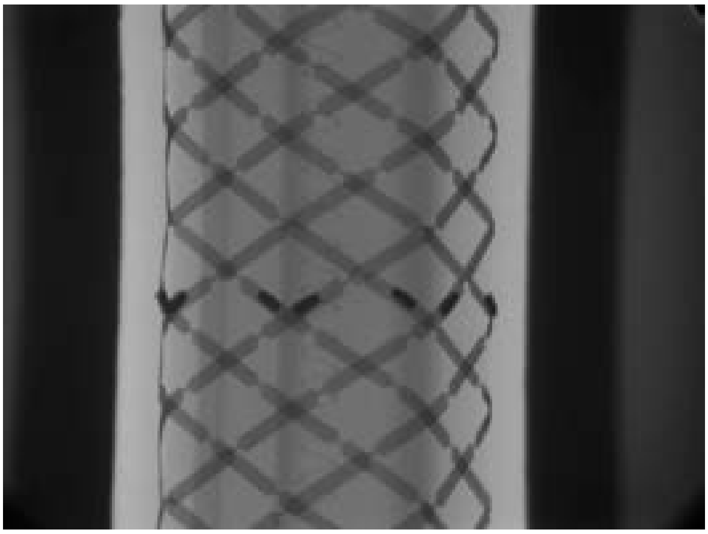


Fig. 4.4.
X-ray image of the fuse with clearly visible fuse-element strips wound on a core.

The core, similarly to the insulating body, is made of electrotechnical porcelain. The element providing galvanic connection between the fuse and the fuse base is the end cap (see Fig. 4.1). The end cap can be made of copper, aluminum or brass. Corrosion protection is obtained by the process of silver, nickel or zinc plating. The selection corrosion protection is a compromise between its effectiveness and the cost of manufacturing. The best corrosion protection is achieved by a silver plating process. Connection between the fuse end cap and the fuse-element can be achieved by pressed-on connection or a welding process and both of these methods are widely used in the high-voltage fuse designs. The pressing method requires tight fitting between the individual components in the fuse, whereas the welding method includes ensuring a uniform connection of two materials in a resistance welding process. The unquestionable advantage of the welding process is obtaining a firm uniform connection. The most widely used extinguishing material in high-voltage fuses is dry quartz sand with grain size below 0.5 mm. In a disturbance situation (overload, short-circuit) the loose extinguishing material deionizes the effects of the electric arc, and during normal operation it provides cooling. The appropriate level of compaction of the extinguishing material inside the fuse is obtained in the process of vibration. High-voltage fuses are offered for operation in indoor and outdoor applications. This means that they can operate under indoor conditions as well as in open air where they are exposed to external weather conditions. The possibility of operation of the fuse in overhead installation conditions is achieved by using the appropriate sealing technology. This design allows a reliable operation of the fuse without the risk of damage. When selecting a fuse, the choice between indoor or outdoor application must be made. Market trends indicate that some producers offer fuses that can operate both in indoor and outdoor conditions. The standard provision of sealing certainly increases the reliability of the offered fuses, also when they are intended for indoor operation. Tightness of the fuse ensures that even if the adverse weather conditions occur like high humidity or condensation, the fuse will continue to provide reliable protection.

4.2. Electrical parameters characterising the fuse-links

The characteristic parameters of fuses which determine both the conditions for testing and use of fuse-links are:

- Rated voltage
- Rated continuous current
- Rated breaking capacity
- Minimum breaking current
- Joule’s integrals
- Power loss
- Time-current characteristics

Rated voltage

The rated voltage of the fuse-link is the maximum voltage at which the fuse-link can operate in a three-phase network. ABB uses two voltage values to mark fuse-links, e.g. 10/24 kV. This means that the offered fuse-link can operate in the grid at voltages from 10 kV to 24 kV, meeting the conditions that are specified by the relevant standard.

Rated current

The rated current is defined as current that can flow through the fuse-link continuously without exceeding the permissible temperatures specified in the standardization documents. ABB in some applications uses a dual current indication e.g. 100_{RC87A}. This marking means that the fuse-link has a time-current characteristic for 100 A, while the value of 87 A means the maximum permissible long-term current that can flow through the fuse. The dual current indication is provided to satisfy the users who use the time-current characteristic as the decisive selection criteria.

Rated breaking capacity

The breaking capacity is the value of the prospective breaking current which the fuse-link is able to break at a specified voltage. The prospective current is expressed as rms value and the typical breaking current values declared by ABB are 16, 25, 40, 50 and 63 kA. The rated breaking capacity is determined for a three-phase grid with directly earthed neutral point, therefore the voltage value during the test is 87% of the rated voltage.

Minimum breaking current

The minimum breaking current is the value of the prospective breaking current which the fuse-link can break at a specified voltage. Unlike the rated

Fig. 4.5.
Graphical interpretation of the Joule's integrals.

Fig. 4.6.
Method for determining the substitute pre-arcing time.

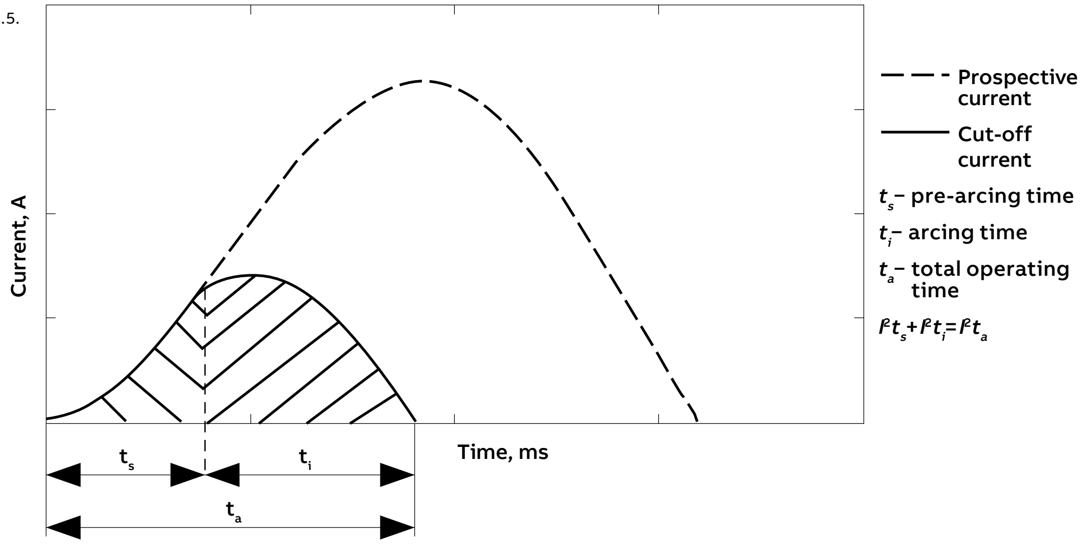
breaking capacity, the value of the minimum breaking current is determined at full power supply voltage. The value of the minimum breaking current depends on the fuse-link class. There are the following classes of high-voltage fuses:

- back-up fuses
- general-purpose fuses
- full-range fuses

Joule's integral

The time-current characteristics provided by the fuse manufacturers constitute the basic information for the selection of a fuse for an application. Use of the actual time before arc ignition is susceptible to a high error which is affected by the switching angle, frequency or time constant of the circuit. In the case of relatively short pre-arcing times (below 100 ms), it is more convenient to use the Joule's integral values which illustrate the thermal effect of the current causing the activation of the fuse. Figure 4.5 shows the graphical interpretation of the Joule's integral. The determination of the integral from the area under the time-current curve during the pre-arcing time can be expressed as Joule's pre-arcing integral, whereas the area under the curve during the arcing time is called Joule's arcing integral. The total energy is the sum of both these integrals and is called the total operating Joule's integral.

Fig. 4.5.



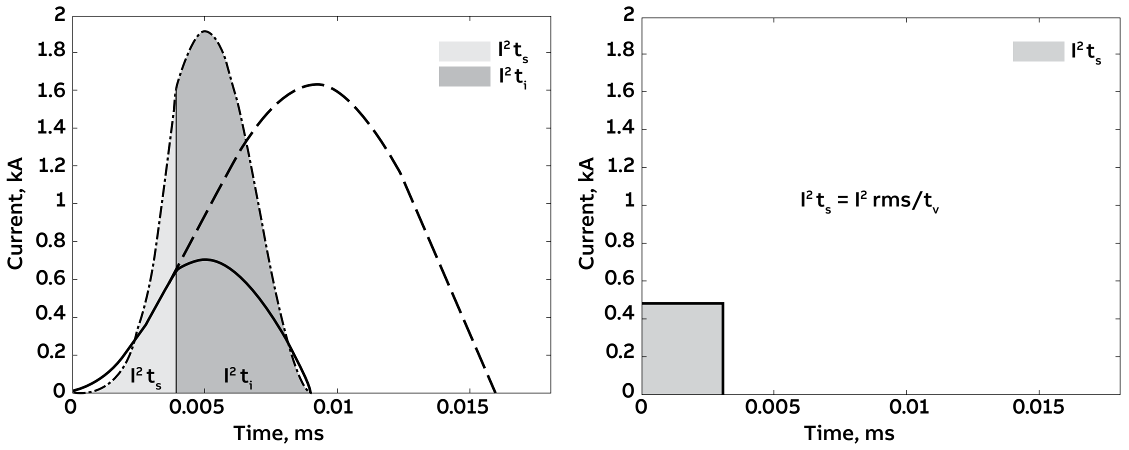
When working with the Joule's pre-arcing integral provided by the manufacturer it can be determined the substitute pre-arcing time using the following formula:

$$t_v = \frac{I^2 t_s}{I^2_{eff}} \qquad 4.1$$

where, I^2t_s – Joule's pre-arcing integral, I^2_{eff} – current rms value, t_v– substitute pre arcing time

Using the dependence presented in the formula 4.1 for a selected current value, it can be specified the substitute pre-arcing time t_v between 1 and 100 ms. For times above 0.1 s, the actual pre-arcing times shall be used. The method of determining the substitute pre-arcing time is shown in Fig. 4.6. The energy released on the fuse, which is essentially the area under the current curve, is presented in the form of a rectangular energy pulse.

Fig. 4.6.



In order to better illustrate the sense of using the Joule’s integrals in the area of low pre-arcing times, the Figure 4.7 shows oscillograms of breaking a 63 kA short-circuit current by the CEF 125 A fuse at different breaking angles. The making current significantly influences the shape of the current curve shape, therefore using the energy is more accurate and delivers lower errors. The fuse-link manufacturers are obliged to specify in the catalogues the minimum pre-arcing integral and the total operating Joule's integral. Both these values can be determined based on breaking capacity tests.

Fig. 4.7.

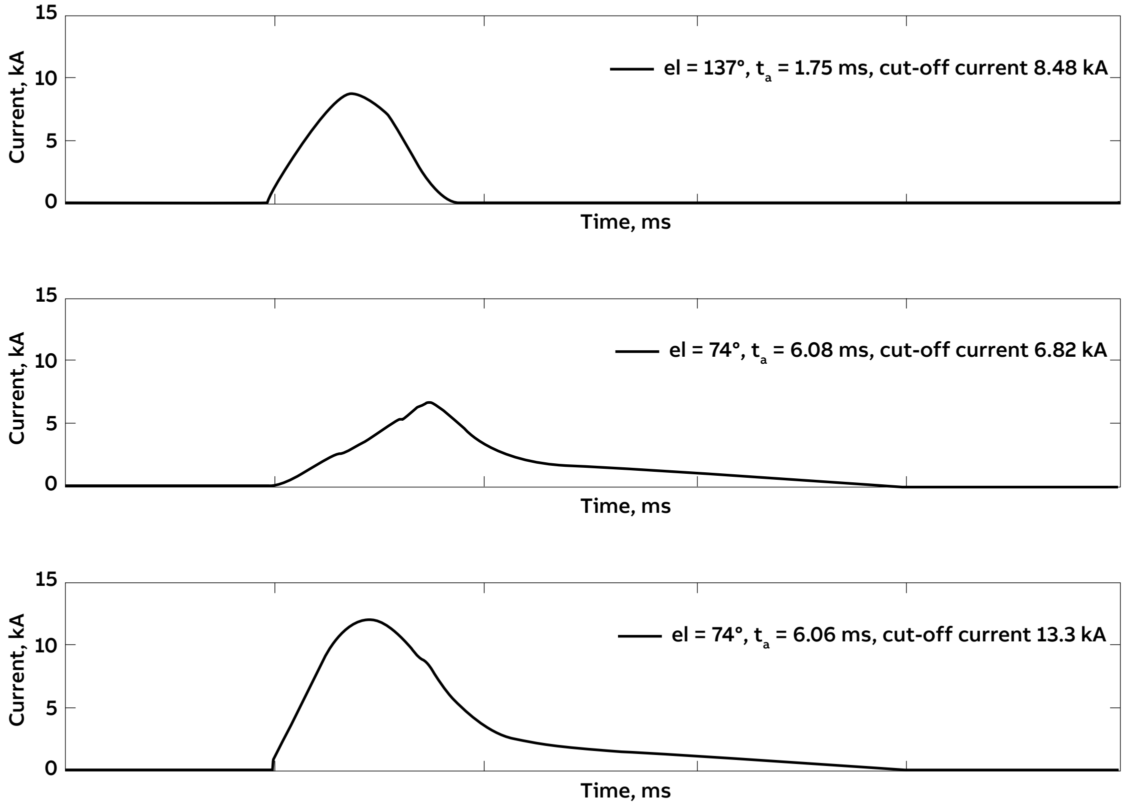


Fig. 4.7.
The effect of the making angle on the current curve shape for the CEF 125A fuse

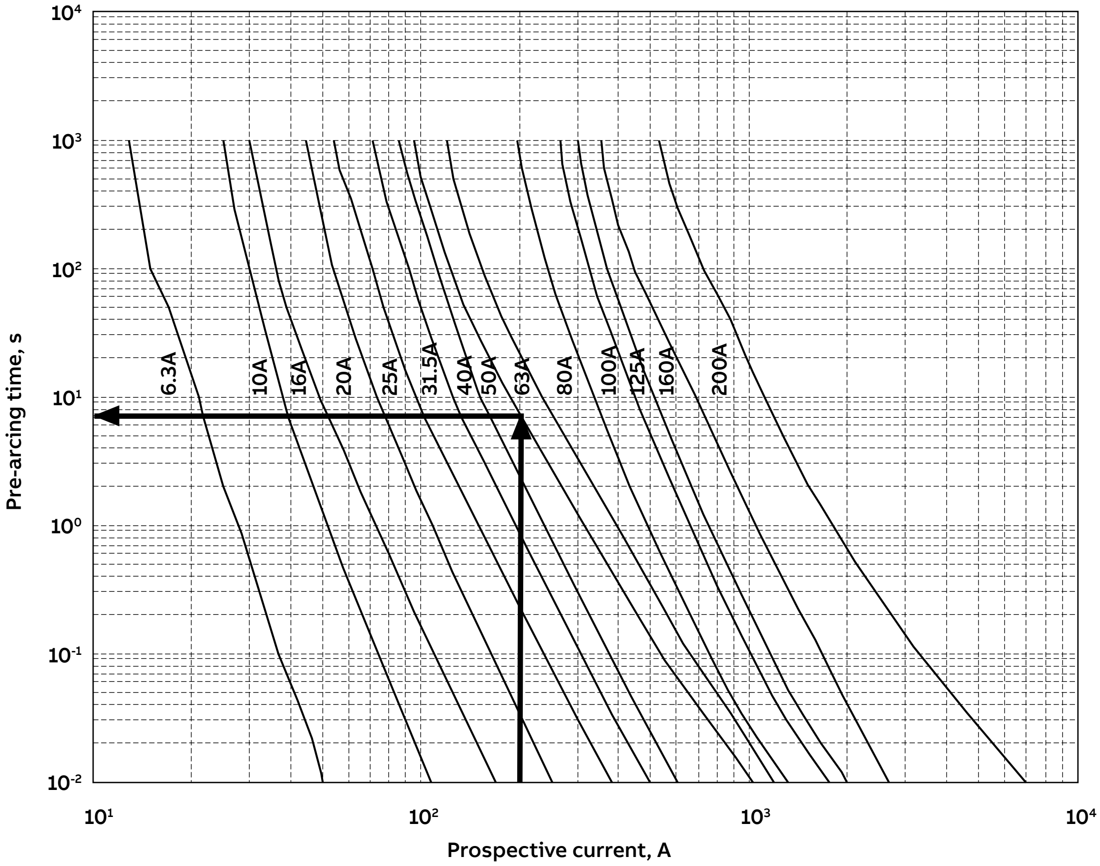
Power loss
The power dissipated in the fuse-link loaded with the rated current. Power loss is determined using a measuring system defined by the standards. Manufacturers are obliged to provide the power loss at 50% and full rated current.

Cut-off current
The highest instantaneous value that the current reaches during the process of breaking by the fuse-link. The value of this current can be read from the cut-off (let-through) current characteristic.

Time-current characteristics
The time-current characteristics show the average pre-arcing times as a function of the prospective current, the current is shown on the X axis and the time on the Y axis. Determination of the characteristic is carried out by loading of a new and previously unloaded fuse-link. The time-current characteristic tolerance allows a deviation of ±20%, however, by controlling the accuracy of manufacturing of the fuse-link it can be obtained a tolerance of ±10%. When determining the time-current characteristics, the actual pre-arcing times are used for times longer than 100 ms, while for times shorter than 100 ms higher accuracy is obtained using Joule’s integrals. The time-current characteristics for the CEF fuse-links are shown in Fig. 4.8. The figure also shows how to read data. In the exemplary case, the pre-arcing time for the CEF 63 A fuse-link loaded with a current of 200 A is 7 seconds.

Fig. 4.8.
Pre-arcing time-current characteristics of CEF 12-24 kV fuse-links and data reading method.

Fig. 4.8.



4.3. The effect of short-circuit current-limiting by a fuse-link

Fig. 4.9.
Current limitation and voltage curve at short-circuit.

Fuse-links that use loose extinguishing material can effectively limit the current value in case of a short-circuit. The effect of the short-circuit current limitation results from the principle of operation of the fuse-link. In the first phase, the flowing short-circuit current melts the fuse-element at narrowings, which causes single arcs to appear at those points. The voltage drop on each partial arc increases rapidly, which causes the voltage on the fuse-link at a certain moment to exceed the mains voltage, which effectively limits the short-circuit current value. The process of short-circuit current breaking is so fast that the current is limited to zero before its natural passage over zero. The effect of the short-circuit current limitation by a fuse-link is explained in Fig. 4.9.

Fig. 4.9.

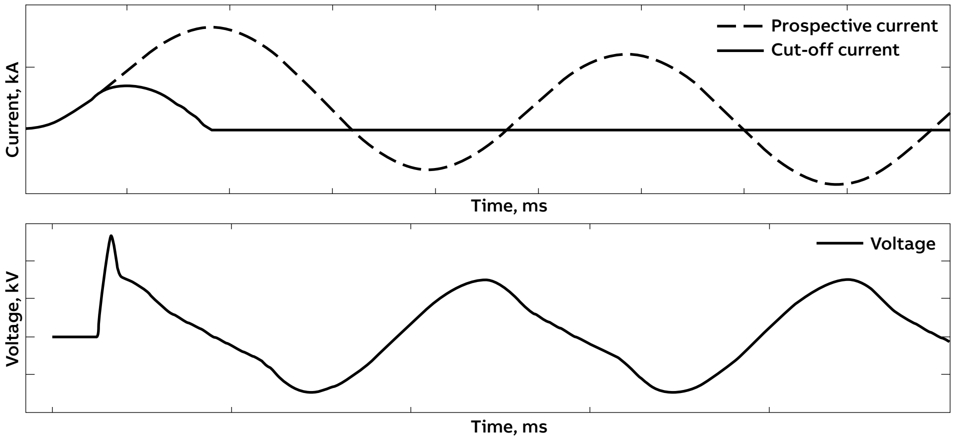


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Fig. 4.10.
Current limitation and voltage curve at short-circuit.

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Fig. 4.11.
Diagram of limited currents for CEF fuse-links.

In the case of the analyzed fuse-links, the time of breaking the current by the fuse is inversely proportional to its value, which means that by increasing the value of the short-circuit current, the time required for its effective interruption is being reduced. The described dependency is clearly visible on the time-current characteristics shown in Figure 4.8. The current and voltage waveforms during the test of short-circuit current breaking by a fuse-link is shown in Fig. 4.10. The figures show that the fuse-link breaks the current before its natural passage over zero.

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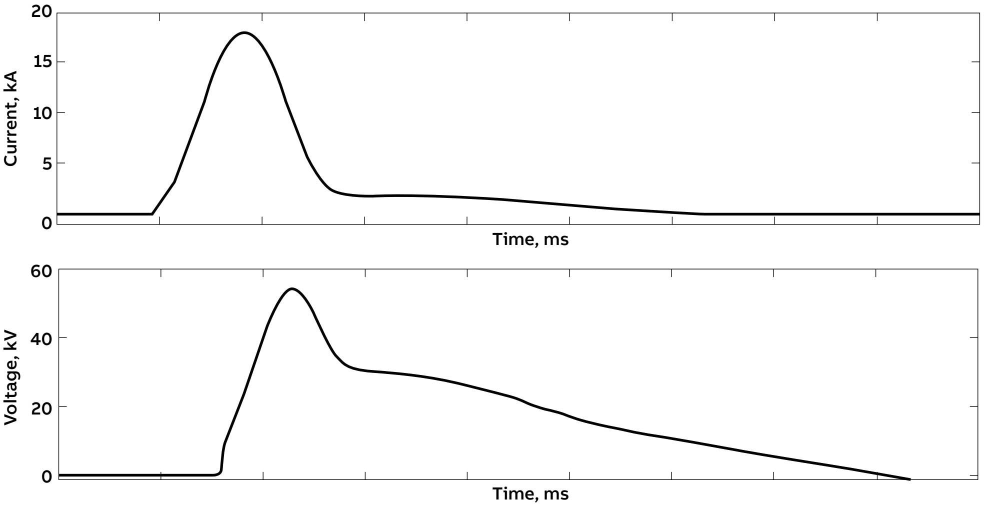
Fig. 4.10.



The capability of limiting the short-circuit currents by the fuses can be shown on the cut-off current characteristic – an example of the cut-off current characteristic for selected fuse-link is shown in Fig. 4.11.

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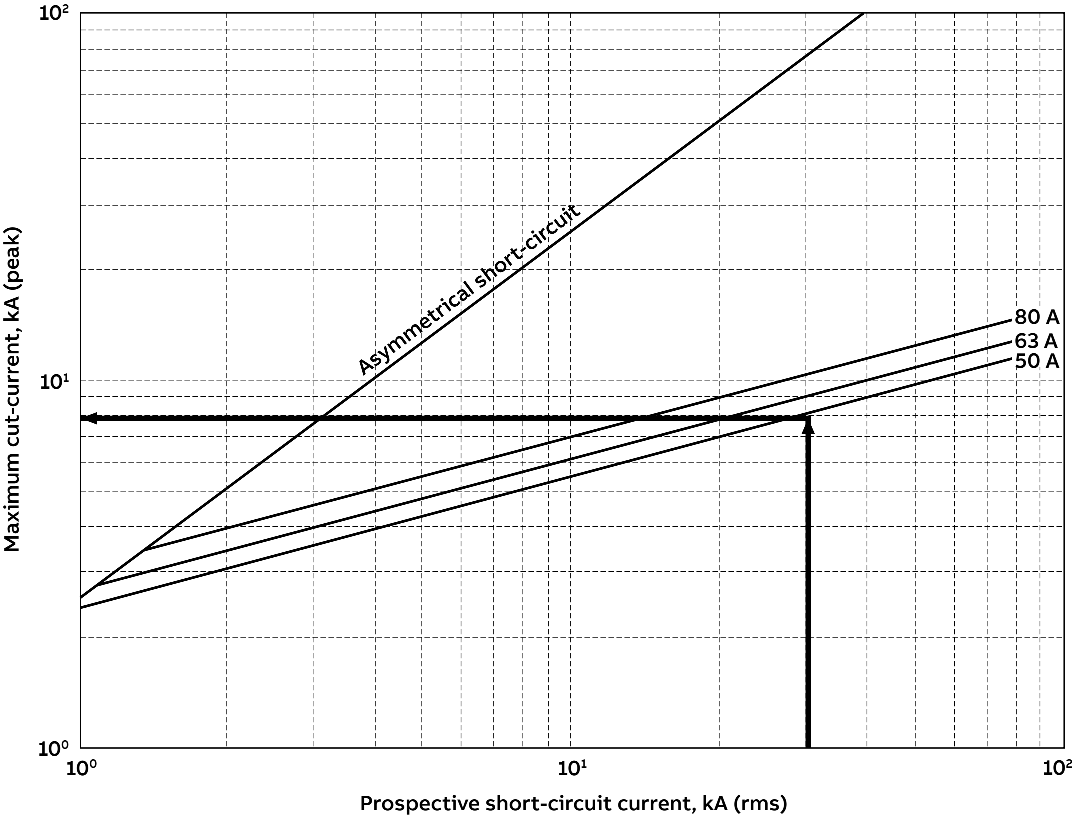
Fig. 4.11.



Based on the presented cut-off current diagram, it can be read that in case of a short-circuit current with an rms value of 30 kA the CEF 50 A fuse will effectively limit the current value to maximum 8 kA. The effect of the short-circuit current-limiting does not occur in the case of overload currents, where the nature of the current breaking process is different.

High-voltage fuse-links are usually made of several strips of fuse-elements connected in parallel. During normal operation, the current flowing through each strip fuse-element is in accordance with the Kirchoff's law. The current distribution in the fuse-link is shown in Fig. 4.12.

Fig. 4.12.

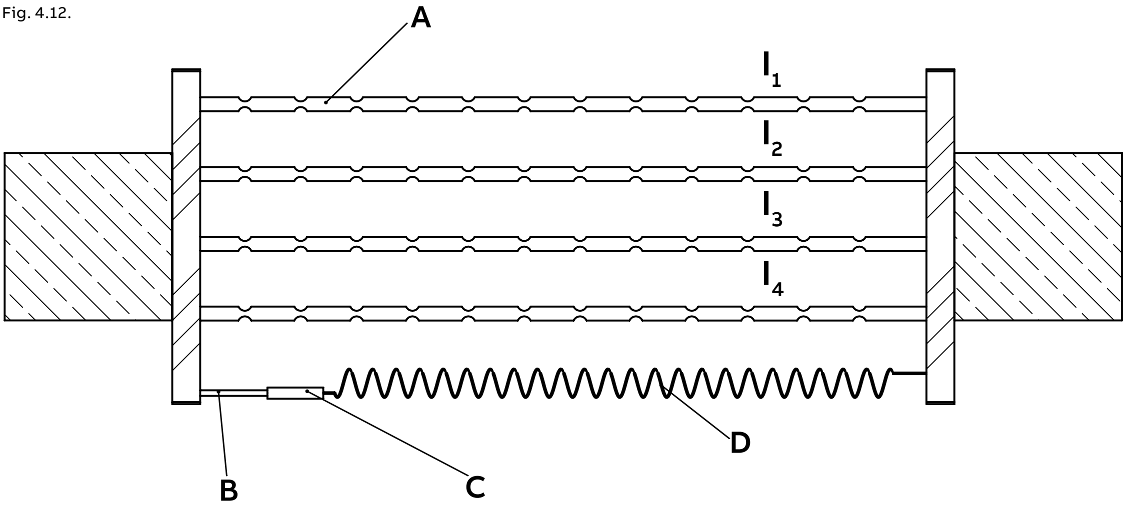


Fig. 4.12.
Current distribution in the high-voltage fuse-link
A – Silver fuse-element
B – Release wire
C – Connection tube in silica sand
D – Striker element embedded
$I = I_1 + I_2 + I_3 + I_4$

When an overload current appears, one of the strips is interrupted. Consequently, the currents in other fuse-elements increase. The significant increase in current values in other fuse-elements results in rapid interruptions of subsequent fusible strips. When the last fuse-element is broken, the circuit is interrupted and electric arc appears. At the initial stage the electric arc is burning in several places along the last fuse-element, but as the arc voltage increases, it moves to a strip of a lower dielectric withstand. The commutation process continues until developing sufficient dielectric withstand to prevent further arc ignitions. The current and voltage waveforms at breaking phenomena is shown in Fig. 4.13.

Fig. 4.13.

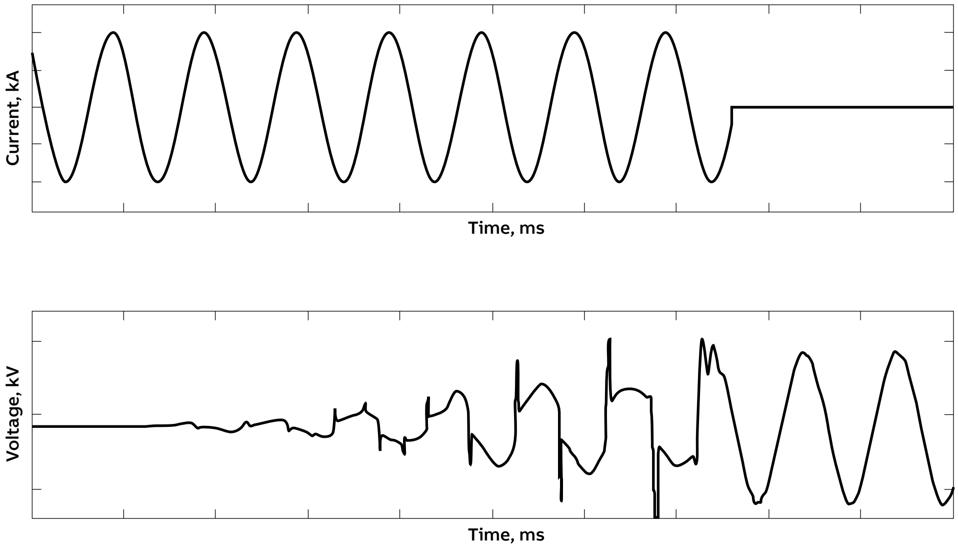


Fig. 4.13.
Current and voltage waveforms at breaking of an overload current.

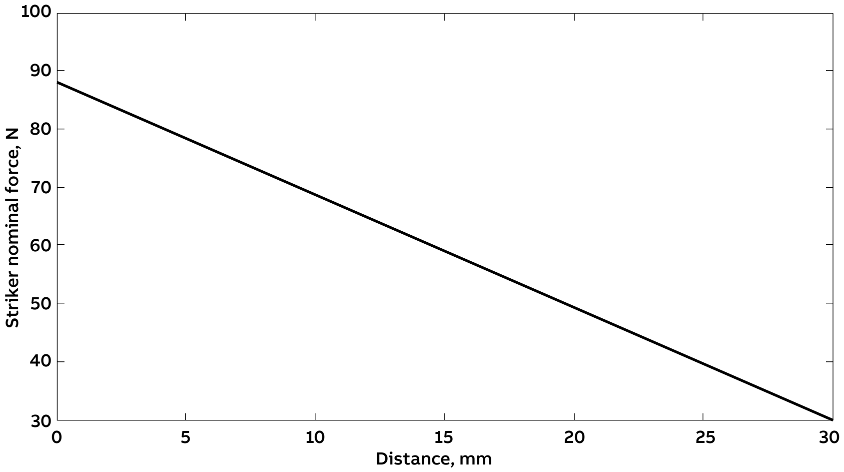
4.4. Fuse-link breaking indication

High-voltage fuse-links can be equipped with a striker system, which may serve as an indicator or a tripping mechanism. The striker is activated by an overload or short-circuit current in the protected circuit, which leads to an interruption of the circuit and consequently to trigger the striker mechanism. The striker mechanism is connected in parallel with the fuse-element and

Fig. 4.14.
Force-distance diagram for the CEF 80 N striker.

has a significant resistance compared to the main path. Thus, under normal operating conditions, the value of the current flowing through the striker circuit is negligible. At the moment of disturbance, i.e. when the interruption of the last fuse-element in the current path occurs, the current commutation occurs and the striker mechanism is triggered providing a specified amount of energy. The striker operating time is several milliseconds, so in case of a short-circuit current, the striker tripping moment is similar to the moment of the main path current breaking by a fuse. In case of overload, the arcing times can reach up to 100 ms, so when the striker is triggered, the fuse-link can carry on the breaking process. According to standard IEC 60282-1 [2], the high-voltage current-limiting fuse-links can be equipped with three types of strikers, depending on the amount of energy that they are able to deliver. There are “light” strikers, whose operation is associated with the visual indication function, and their force is not determined.
The “medium” strikers are the most popular in high-voltage fuse-links. The force-distance diagram for fuse-links equipped with a “medium” striker for the spring holding force of 80 N is shown in Fig. 4.14.

Fig. 4.14.



The last striker group are the “heavy” strikers used in special solutions, e.g. oil-submerged fuse-links installed in the transformer tank and protecting against the effects of an internal short-circuit. The described mechanical characteristics of the strikers are given in detail in Table 4.1.

Table 4.1. Mechanical characteristics of strikers.

Fuse	Energy, N	Idle stroke, mm	Operating stroke, mm	Total absolute stroke, mm	Minimum impact force, N
Light	0.3 ±0.25	2	8	30	NA
Medium	1 ±0.5	4	16	40	20
Heavy	2 ±1	4	6	16	40

To make the striker activation more visible, ABB marks all strikers with red color to facilitate identification of the activation. The “medium” and “heavy” strikers have standardized energy value, so that the fuse-link with such a striker type can cooperate with a switch-disconnector. Cooperation of a fuse-link with a switch-disconnector is described in section 4.6.
Fuse-links are characterized by a significant resistance compared to other equipment comprising the power system, which results in significant heat emission. Temperatures that may appear on a fuse-link in steady state conditions are provided in standardization documents and normally do not cause any malfunctions of the systems. Exceeding the permissible temperatures can occur in case of a prolonged overload, and the amount of heat generated can impair the safety of the fuse operation and the devices cooperating with it. To prevent this effect, the fuse-link manufacturers develop individual solutions which, in combination with the striker, give a signal to opening the circuit by another device, e.g. switch-disconnector. The TCU (Temperature Control Unit) used by ABB is a thermal trigger integrated with the fuse-link striker, which

operates when the specified thermal conditions are exceeded. When the temperature is too high, the TCU releases the striker which activates the switch-disconnector opening system. The diagram presenting the TCU operating range is shown in Fig. 4.15.

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Fig. 4.15.

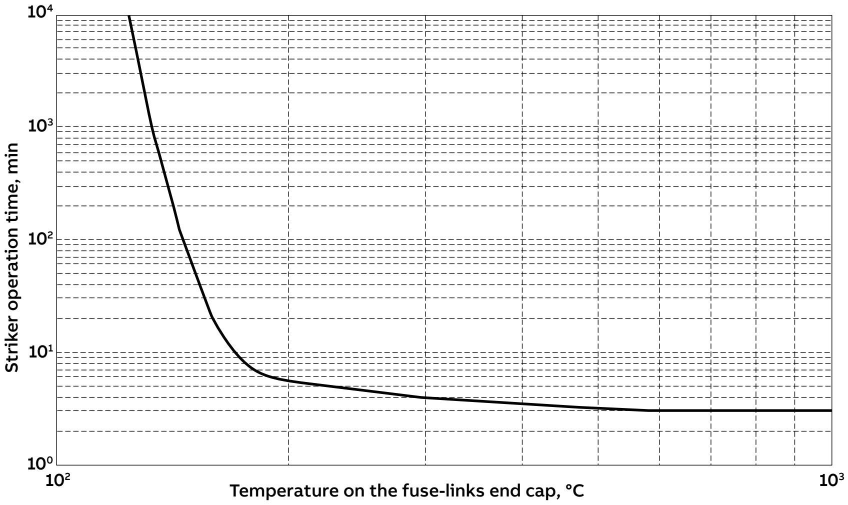

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Fig. 4.15.
TCU operating parameters.

4.5. Selecting a fuse-link for application

This section presents the main equipment that can be protected by high-voltage current-limiting fuses.

Transformer protection
The main area of application of the high-voltage fuses is protection of the transformers against short-circuits and overloads. The selection methodology for high-voltage fuse-links is given in IEC/TR 62655 [4]. According to the recommendation of this standard, the fuses links are selected to reduce the negative effects of short-circuit or overload in the transformer. The principle of fuse-link selection for transformer protection is shown in Fig. 4.16.

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Fig. 4.16.

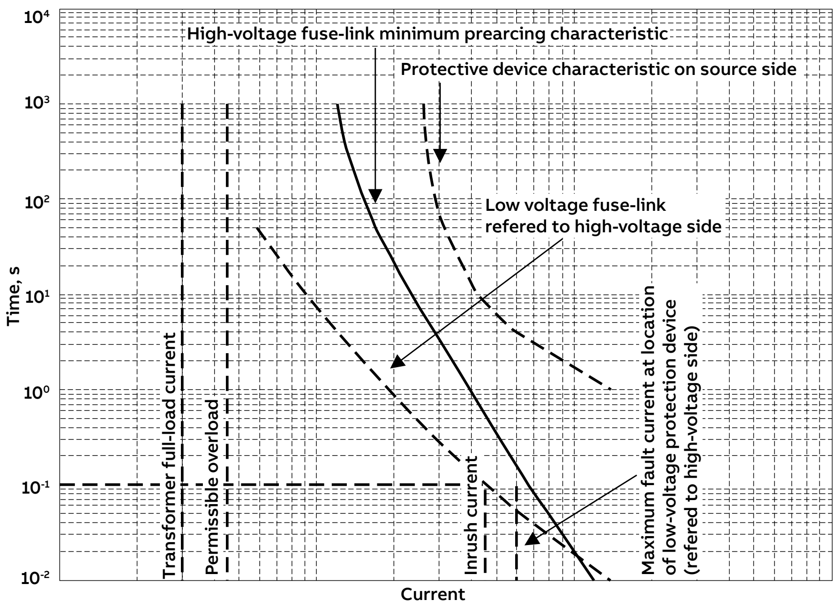

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Fig. 4.16.
Principle of fuse-link selection for transformer protection.

According to the plotted curves, it can be set the main criteria that are used for selection of transformer protection fuse-links:

- The fuse-link must not break under the condition of the transformer rated current.
- The fuse-link must not break under the condition of permissible overload current.
- The transformer inrush current that appears during transformer energization must not lead to breaking of the fuse-link.
- In case of a short-circuit at the terminals of the transformer secondary side, the fuse-link on the high-voltage side should break the circuit as quickly as possible, limiting the negative effects of the fault condition.

For simplification reasons, manufacturers provide properly selected fuse-links in their catalogs, depending on the transformer protection parameters. Table 4.2 shows the selection of ABB fuse-links to protect selected MV transformers.

Table 4.2. Selection of ABB fuse-links for MV transformer protection

	Rated transformer power, kVA									
Rated voltage, kV	**100**	**125**	**160**	**200**	**250**	**315**	**400**	**500**	**630**	**800**
	Fuse-link, A									
6	20	20	31.5	31.5	40	50	50	100	100	100
10	16	16	20	20	25	32.5	32.5	50	50	63
12	10	16	20	20	20	25	32.5	40	50	50
15	10	10	16	16	20	20	25	32.5	40	40
20	10	10	16	16	16	20	20	25	32.5	32.5
24	6.3	10	10	10	16	16	20	20	25	25

When selecting a fuse-link for transformer protection other criteria should also be considered, such as the rated voltage of the fuse-link, the minimum and maximum breaking current. The rated voltage of the fuse-link must be equal to or higher than the line-to-line voltage of the system. When selecting the rated voltage of the fuse-link, make sure that the maximum electric arc voltage does not exceed the insulation level of the given grid (system). In case of the breaking current, the fuse-link must be characterised by a current equal to or greater than the current that may result from the grid configuration. The fuse-links manufactured by ABB are tested in a circuit with an asymmetric short-circuit current of 63 kA for voltages 7.2 kV – 24 kV. Please note, that the specified maximum short-circuit current is given as rms. value, which means that the maximum value is 157.5 kA. Of course, the fuse-link, due to its specific features, effectively limits the short-circuit current level.

Capacitor bank protection

In a power grid, the capacitor banks are used to improve the power factor. The capacitor banks currently used are characterised by relatively high power, therefore there is a need for protection against potential overload or short-circuit. The protection strategy of the capacitor banks results from their configuration in the system. In high-power systems, single-phase capacitors are connected in selected configurations, e.g. star or delta connection.

When selecting a fuse-link to protect a capacitor bank, special attention must given to such parameters as the rated voltage and rated current. The rated voltage of the selected fuse-link shall be equal or higher than the highest voltage that may occur during a disturbance condition. In the case of capacitor banks, the voltage value may be doubled, because there is a risk that the fuse-link will “see” the full voltage existing on the capacitor bank plus the reversely polarized grid voltage. When selecting a fuse-link for such an application, it must be considered that the rated voltage should be at least twice the grid voltage.

The process of energization of capacitors banks is accompanied by extreme high transient inrush charging currents, which may be reduced by insertion of inductance, for example in a form of current-limiting reactors. These reactors may also reduce the negative impact of higher harmonics. When selecting a fuse-link it must be ensured that it will not break during switching processes and will react at overload or short-circuit conditions. When selecting a fuse-link it must be ensured that its pre-arcing Joule’s integral will be greater than the energy generated during the capacitor bank energization. The energy released during the energization of the capacitor bank can be determined using the following formula:

$$I^2t = 3.74E^2C^{2/3}L^{-1/2}A^2s$$

where:

E – is the phase to ground peak in volts, V
C – is the phase capacitance of bank in farads, F
L – is the source circuit inductance in henries, H

The engineering practice requires that the rated current of the fuse-link is twice higher than the current expected at operating conditions.

Voltage transformer protection

Voltage transformers in a power grid perform a function of a power source for measuring and protection systems. The idea of the VT protection on the medium-voltage side by means of a fuse-link assumes that in case of a failure, the VT will be disconnected from the power system.
This allows the system to continue to work, while the failed VT is cut off from the grid.
The rated power of a VT is several tens of VA, which means that the high-voltage current level is very low. The fuse-links offered by ABB for the protection of voltage transformers are characterized by the rated current value of 0.5 A to 6.3 A. When selecting a fuse-link for a VT protection, the corresponding rated voltage and rated current shall be chosen. The rated voltage of the fuse-link shall be equal to or higher than the rated voltage of the protected device. When selecting a fuse-link that features higher rated voltage than the protected object, make sure that the switching overvoltage generated by the fuse-link are acceptable. The selection of the rated current is always a compromise between the fuse sensitivity to transient states, e.g. during the energization process, and the zone of the reliable operation of the fuse-link.
When selecting a fuse-link, it must be ensured, that it will not break during the process of connecting the VT to the grid, and at the same time, that in case of an emergency condition, the fuse will be able to react quickly to the grid disturbance.

High-voltage motor protection

The conversion of electric energy into mechanical is the foundation for the contemporary industry. High-voltage electric motors are used for the drive of fans, compressors, crushers, pumps. Protection of high-voltage motors against short-circuits or overloads may be carried out by using fuse-links. Fuse-links with their unique properties may constitute a reliable protection. Among the advantages are the possibility of limiting short-circuit currents, extremely fast breaking time and operational reliability.
In contrast to the previously described protection applications, in case of electric motors, mechanical energy that occurs here may increase the negative effects of the failure. Using high-voltage fuse-links, it can be provided a cost effective protection for the grid to which the motor is connected, as well as for the mechanical devices cooperating with it.
The protection of high-voltage motors requires introduction of methods to support customers in selection of fuse-links for their applications. Particularly, special attention need to be paid to the motor starting inrush currents. The fuse-link must not be sensitive to this type of transient states. In case of a direct start-up (direct on line), the starting current may be up to eight times greater than the rated current. A significant limitation of inrush currents can be achieved by using soft starting equipment based on power electronics designed for this purpose. Soft start motors can be protected by a fuse-link with a much lower rated current.
The IEC 60644 [1] standard taking the topic of fuse-links used for motor protection introduces a safety factor K lower than one. This factor defines the correct operation of the fuse-link during subsequent start-ups. The factor K, which essentially is a curve, should be located between the motor current curve and the time-current characteristic of the used fuse-link. The correlation between these values is shown in Fig. 4.17.

Fig. 4.17.

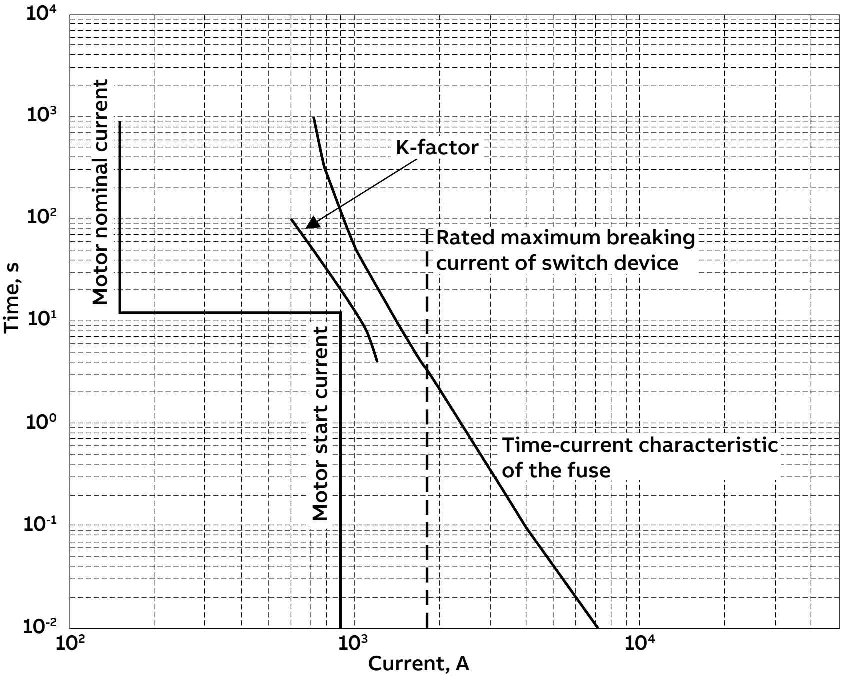
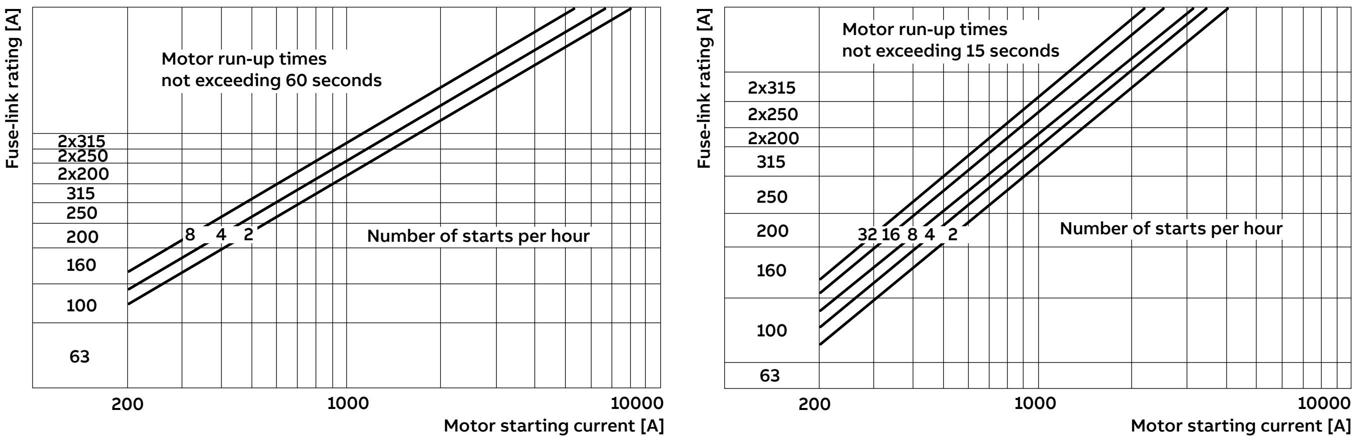


Fig. 4.17. Characteristics relating to the protection of motor circuit.

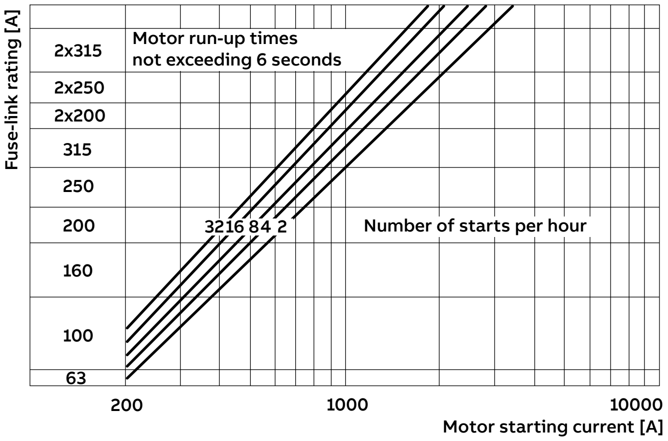
Fig. 4.18.
Charts used for selection of CMF fuse-links for motor protection.

ABB offers the CMF fuse-links for motor protection. The maximum permissible rated current of that type can be determined from the corresponding diagrams No. 1, 2 and 3. (see Figure 4.18). Three different diagrams are used for motor starting times within 6, 15 and 60 seconds respectively. Each chart contains different characteristics corresponding to different number of motor starts per hour.
For a given number of motor starts per hour it is assumed that the first two start-ups are performed immediately one by one, and the rest are distributed evenly within one hour. The number of motor starts per hour indicates the time interval between the subsequent starts. For example, when there are 4 starts within 15 minutes, it is assumed that there are 16 starts per hour. The horizontal axis of the fuse-link selection chart shows the motor starting current, and the rated current of the fuse-link can be read from the vertical axis of the chart.

Fig. 4.18.


Selection chart No. 1:
Selection chart No. 2:

Selection chart No. 3:



Selection procedure:
Step 1: Select the diagram corresponding to the actual starting time of the particular motor for which the fuse-link will be installed.
Step 2: Find the value corresponding to the starting current of this motor on the horizontal axis of the chart.
Step 3: Depending on the assumed number of motor starts per hour, select the appropriate curve on the chart (corresponding to 2, 4, 8, 16 or 32 starts per hour).
Step 4: Find the intersection of starting current with the curve specifying the number of starts and read the correct fuse-link rating on the vertical axis.
Two examples, A and B of a CMF fuse-link selection is shown in Table 4.3.

Table 4.3. Example of a fuse-link selection depending on the parameters.

Example	A	B
Motor starting current	850 A	250 A
Motor starting time	6 sec	15 sec
Number of starts per hour	2	16
Chart number	3	2
Fuse-link rated current (A)	250	A

4.6. High-voltage switch-disconnector with fuses

Fig. 4.19.
NALF – switch-fuse combination

The most popular form of transformer protection against disturbance conditions is a combination of a fuse-link and a switch-disconnector in a three-phase system. This means that the set consists of a switch-disconnector connected in series with a fuse-link. With this combination, it is possible to provide a “full range disconnecting device”. With the switch-disconnector and its visible safety break in the circuit, it is possible to perform maintenance activities. The cooperation of both devices is achieved through the use of strikers which give a tripping signal to open the switch-disconnector.

In case of overload, the current interruption function is carried out by the switch-disconnector which gets the tripping signal from the striker. Please note, that the striker tripping operation is not equal to the interruption of the current by the fuse-link. This is because the striker is triggered when the fuse-link circuit is interrupted, so the arc extinguishing process may still be in progress. The second scenario assumes activation of a TCU limiter (temperature control unit) that is mounted as standard in all CEF fuse-links. The limiter is integrated with the striker and triggers it in case of excessive temperature rise in the fuse area. Such situation can happen when the fuse-link is used in enclosed switchgear tubes insulated with SF6 gas.

In case of short-circuit, the current interrupting function is fully taken over by the fuse-link. The fuse-link breaking time, which can be a few milliseconds, is fast enough that in case of a short-circuit in all phases the switching device opens in a current-free condition.
The current value that differentiate activation of switch-disconnector or fuse-link is called the transfer current. This current must be lower than the switching capacity of the switch-disconnector. Below the transfer current, the switching role is taken over by the switch-disconnector, while above the transfer current level, the disturbance is interrupted by the fuse-link. In order to protect the transformer, the fuse-link must be properly selected, as well as the switch-disconnector which will cooperate with it. A sample selection of the fuse-link for the transformer is given in Table 4.2, and such information is typically provided by the fuse manufacturers.
Determination of the transfer current for the given set requires the knowledge of the time-current characteristic of the concerned fuse-link and the switch-disconnector parameters, such as the opening time T_0, and the switch-disconnector transfer current. The NALF switch-disconnector with fuse offered by ABB is characterized by a 50 ms opening time and a 1600 A transfer current. A detailed methodology that allows to determine the transfer current for the assumed parameters is given in the standardization document IEC 62271-105 (High-voltage switchgear and controlgear – Part 105: Alternating current switch-fuse combinations for rated voltages above 1 kV up to and including 52 kV) [5].

The methodology for determining the transfer current can be described according to the following iteration:
- Using the **minimum** time-current curve of the analyzed fuse-link, determine the approximate current value and for this value, read the operation time T_2
- The determined current value is brought to a two-phase short-circuit, i.e. this current is reduced to 87% of its value. For this current value, check the crossing point with the **intermediate** time-current characteristic and read the time T_1
- Check the differences between the times T_2 and T_1, and it should be equal to or less than time T_0
- Repeat the operation until finding the appropriate current value, which is denoted as the transfer current

Fig. 4.19.

The method of selecting a fuse-link for protection of an 800 kV transformer is presented in the example below.

Example 4.1

According to Table 4.2, the CEF 12 kV 63 A fuse-link is selected. In Table 4.4 the transfer current is compared for the switch-disconnector and the fuse-link.

Table 4.4. First condition. Comparison of transfer current for switch-disconnector and fuse-link

Fuse-link transfer current	Switch-disconnector transfer current	Selection result
840 A	1600 A	Correct

Another condition resulting from the standardization documents requires checking whether the transformer short-circuit current resulting from its impedance is greater than the fuse-link transfer current. The results are shown in Table 9.2, assuming that the transformer short-circuit voltage is 4%.

Table 4.5. Second condition. Comparison of transformer short-circuit current and the fuse-link transfer current.

Fuse-link transfer current	Transformer short-circuit current	Selection result
840 A	1155 A	Correct

The method of determining the transfer current for the switch-disconnector type NALF and the CEF 63 A fuse-link is shown in Fig. 4.20.

In the analysed example both criteria are fulfilled and the set of a switch-disconnector with fuse provides a full-range transformer protection function. If there are difficulties with fulfilment of these conditions, ABB has a family of CEF-S fuse-links in its portfolio, which are characterised by a “faster” time-current characteristic than the previously analysed CEF fuses. Due to the fact that the characteristics of these fuses are faster with the same rated current, the transfer current of this fuse is relatively lower.

Using a back-up protection fuse-links in combination with a switch-disconnector, it is necessary to take into account the situation in which the fuse-link will break in an uncertain operating zone, i.e. the current value that will break the fuse circuit will be lower than its minimum breaking current. As such situation may occur, the standardization documents require the manufacturer to declare that the fuse-link will be able to withstand the internal arc for a minimum of 100 ms without visible external damages. The fulfilment of this condition ensures that the circuit is safely interrupted by the switch-disconnector in extremely adverse conditions. ABB is able to guarantee that the high-voltage fuse-links it produces meet this criterion. Figure 4.21 shows an oscillogram presenting voltages on the fuse-link during the arcing strength test.

Fig. 4.21.

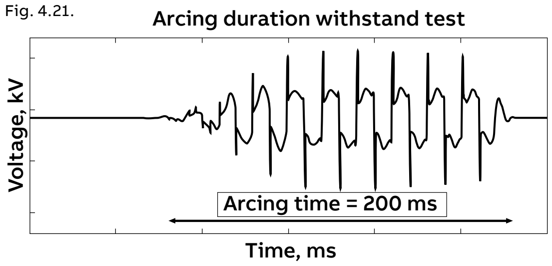


Fig. 4.21. Oscillogram of the CEF 63 A fuse-link short-circuit withstand test.

Fig. 4.20.

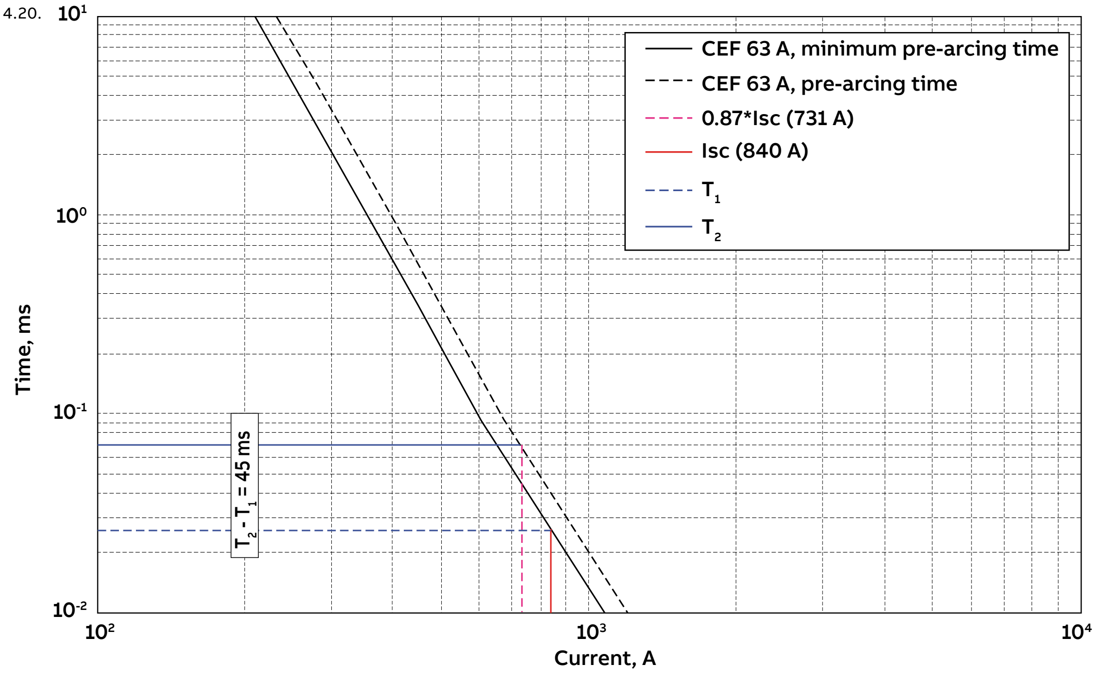


Fig. 4.20. Method of determining the transfer current for the analysed apparatus and the CEF 63 A fuse-link.

4.7. Parallel connection of fuses

The high-voltage fuse-links available on the market are characterised by rated currents up to 315 A, which constitutes a certain restriction when the application requires use of higher operating currents.

Individual fuse-links of the same type and same ratings may be combined in parallel to obtain a higher rated current than it would be possible to obtain from single fuse. Selecting fuse-links requires meeting certain criteria to ensure proper operation of the fuse in both steady states and disturbance conditions:

- Fuse-links must be of the same type and from one manufacturer
- The rated current of parallel connected fuses will typically be slightly lower than the sum of rated currents of individual fuses due to the heating caused by their proximity
- The minimum distance between fuse-links shall not be less than 20 mm
- The wires connecting individual fuses shall have the same resistance, so that the operating currents flowing through individual fuses have the same values
- Parallel connection of fuse-links requires introduction of new technical parameters describing the set
- The value of the Joule's integrals during operation of parallel connected fuses can be calculated using the $I^2t = n^2\mathrm{x}(I^2t)$ equation, where *n* is the number of fuse-links connected in parallel
- The value of the cut-off for fuse-links connected in parallel shall be approximately equal to *n* x cut-off of a single fuse-link, assuming that the prospective current is proportionally divided by the number of parallel fuses, where *n* is the number of fuse-links connected in parallel. The diagram presenting the concept of determining the cut-off is shown in Fig. 4.22
- The maximum breaking current is equal to the breaking current of a single fuse-link, unless the manufacturer declares higher values
- The minimum breaking current is not less than *n*-times the breaking current of the smallest single fuse of the same type, where *n* is the number of parallel fuses

The time-current characteristics of the fuses connected in parallel can be determined by *n*-time offsetting the time-current characteristic of a single fuse, where *n* is the number of parallel fuses. Figure 4.23 shows the method of determining the time-current characteristic in the case of parallel connection of two or three fuse-links type CEF 200 A.

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Fig. 4.22.

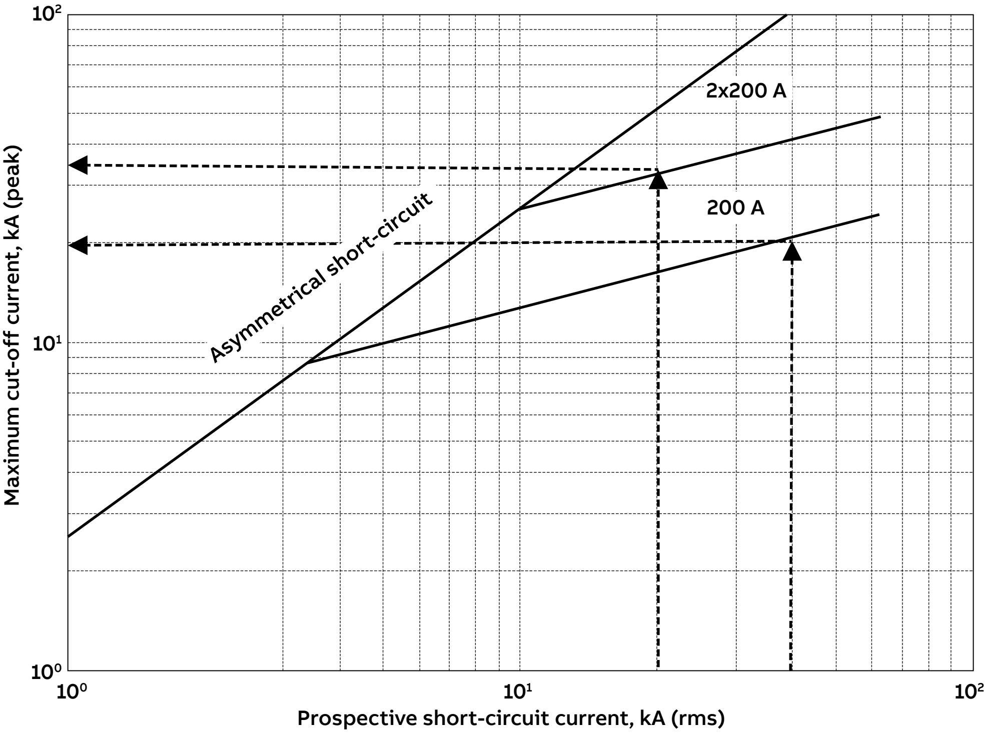

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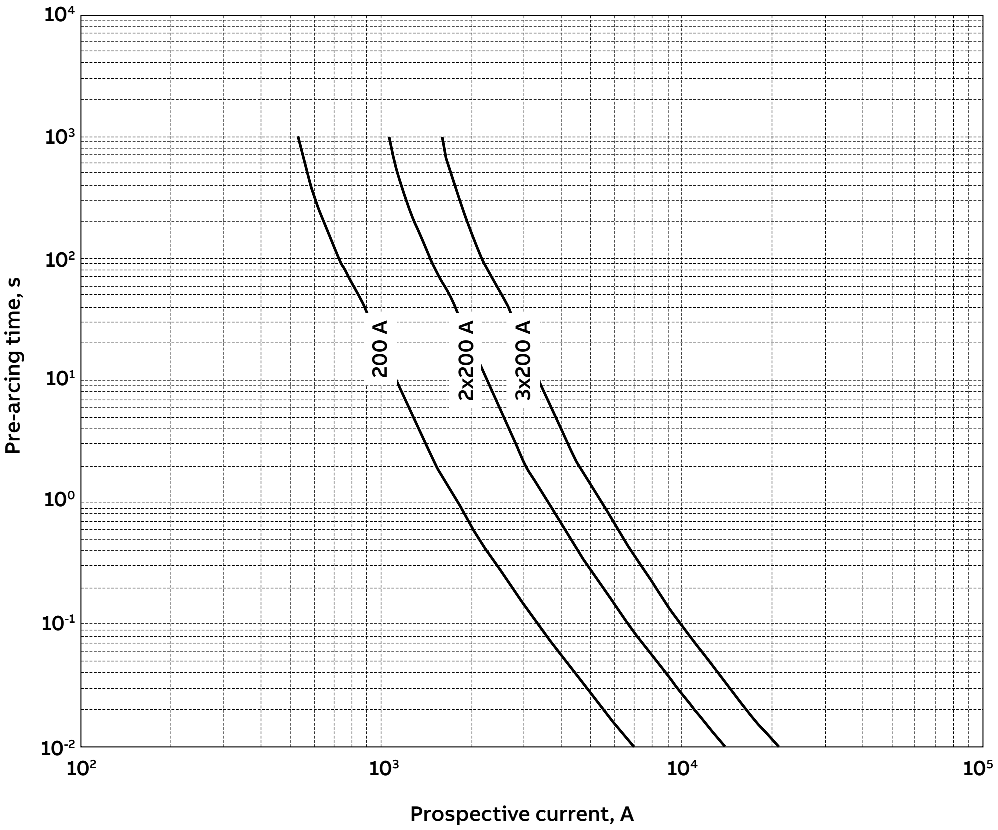
Fig. 4.22.
Chart presenting the method of determining the cut-off for the CEF 200 A fuse-link. For a prospective current of 40 kA, and when the maximum value of the limited current for single fuse-link is 20 kA, in the case of two fuse-links connected in parallel for the same prospective current value, the limited current is increased to a maximum value of 35 kA.

Fig. 4.23.
Chart of the time-current characteristics in case of parallel connection of CEF 200 A fuses.

Fig. 4.23.



4.8. De-rating of fuse-links

High-voltage fuse-link are subject to temperature tests which result from the relevant standards. The fuse-link is placed in a free space in the position resulting from its natural operation. The standard accepts the maximum ambient temperature of 40°C and maximum temperature rise on fuse-link contacts of 65°C. This means that the maximum temperature of the fuse current path must not exceed 105°C. If air is used as the insulating medium, tests are carried out in a dedicated fuse base and in open space. For the fuse-links intended for operation submerged in oil a special test device filled with liquid is provided.

When fuses are used in enclosed switchgears, temperature rises can be higher than the permissible due to the vicinity of other fuse-links and the limited heat exchange with the surroundings. In such a situation, it may be necessary to reduce the rated current to a value that will not result in exceeding the permissible temperature rise, which is the so-called de-rating of a fuse-link. The correction factor is essentially the ratio of the maximum operating current to the rated current of the fuse-link.

Due to the variety of applications in which fuse-links are used, laboratory tests are the optimal method of determining the maximum operating current.

De-rating may also appear to be necessary when a fuse-link is exposed to operation at ambient temperature exceeding 40˚C. Examples of such situations include: fuse-link installed inside the transformer tank, or in other equipment that may generate a lot of heat, as well as situations related to strong sunlight or high ambient temperatures.

4.9 Guidelines for handling fuse-links

Transportation and storage
The fuses shall always be transported in the packaging. Usually fuse-links are packed individually in carton packaging, and collectively in bigger boxes. When transporting consignments with fuses, special attention need to be paid to the information signs on the packaging and appropriate protection of cargo against shocks and humidity must be ensured. Fuse-links must be stored in a dry place, at temperatures from -25º C to 50°C and relative humidity not exceeding 85%. The surrounding air must not be significantly contaminated by dust, smoke, corrosive or flammable gases and salt vapours.

Installation and replacement
Before installation of fuse-link in each circuit phase, the following points shall be checked:

- The fuse-link is not damaged, there is no sand inside the fuse packaging.
- The data on the nameplate and the fuse dimensions are in accordance with the technical documentation of the circuit or identical to the data of the fuse to be replaced. The fuse is selected according to IEC 60282-1, chapter 9.
- The measured fuse-link resistance is conforming with the ABB catalogue data, or with the documentation supplied with fuses. The resistance shall be measured with a miliohmmeter, at ambient temperature of approx. 20ºC.
- The fuse base contacts and connections are in good condition, protected with acid-free vaseline, insulators are free from dirt.
- It is recommended to replace the fuse-links in a voltage-free condition of the circuit.
- If the fuse is installed within a switch-disconnector, it is suggested to perform a switch-disconnector tripping test using a test fuse-link, before the fuse-link is installed or replaced.
- After installing the fuse, make sure that the fuse-link is correctly mounted in the fuse base contacts, and that the striker is directed towards the tripping or signalling device.
- According to IEC 60282-1, it is suggested to replace all three fuse-links in a three-phase network, even if only one or two fuse-links were blown, unless it is guaranteed that no disturbance current has passed through the other fuse-links. The above-mentioned disturbance current may significantly affect the electrical characteristics of the fuse-link which can be the cause of future failure.
- Use of different types of fuse-links in one three-phase set (i.e. different classes and/or from different manufacturers) is not recommended, even if they have the same data on the rating plates.

Inspections and maintenance
The fuse-links generally do not require special inspections and maintenance and do not wear during their operation under normal environmental conditions (described in IEC 60282-1, chapter 2). It is recommended that the inspections of the fuse-links and fuse bases are carried out during periodic inspections of other electrical equipment located in the switchgear, in accordance with their inspection intervals. During the voltage-free inspection it is recommended to perform the following:

- Cleaning of porcelain tube of the fuse-link and the insulators of the fuse base
- Cleaning of the fuse base contacts and connections, applying acid-free vaseline protection coating
- Bolt tightening
- For special operating conditions of fuse-links, inspection and maintenance conditions shall be agreed with the manufacturer

5. References

1. IEC 60644:2009 – Specification for high-voltage fuse-links for motor circuit applications.
2. IEC 60282-1:2009 Amd1: 2014 – High-voltage fuses – Part 1: Current-limiting fuses.
3. IEC 60549:2013 – High-voltage fuses for the external protection of shunt capacitors.
4. IEC/TR 62655: 2013 – Tutorial and application guide for high-voltage fuses.
5. IEC 62271-105:2012 – High-voltage switchgear and controlgear – Part 105: Alternating current switch-fuse combinations for rated voltages above 1 kV up to and including 52 kV.
6. IEEE C37.40: 2003 – Standard service conditions and definitions for high-voltage fuses, distribution enclosed single – pole air switches, fuses disconnecting switches and accessories
7. IEEE C37.41: 2008 – Standard design tests for high-voltage (>1000 V) fuses, fuse and disconnecting cutouts, distribution enclosed single – pole air switches, fuse disconnecting switches, and fuse-links and accessories used with these devices.
8. IEEE C37.42: 2009 – IEEE Standard Specification for high-voltage (>1000 V) expulsion-type distribution-class fuses, fuses and disconnecting switches, and fuse-links, and accessories used with these devices.
9. IEEE C37.48.1: 2000 – Guide for application, operation, and coordination of high-voltage (>1000 V) current-limiting fuses.

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