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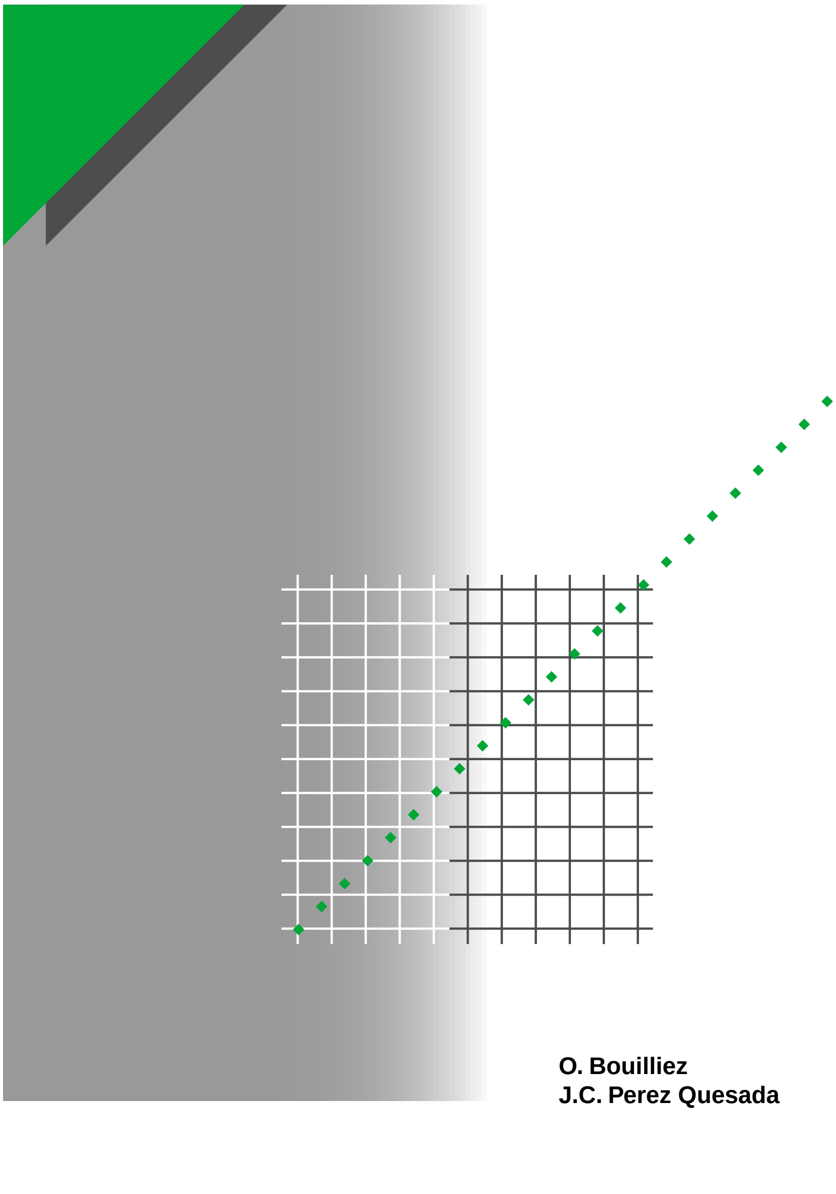
Design and use of MV current-limiting fuses



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no. 128

Design and use of MV current-limiting fuses

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Lexicon

I1	Maximum breaking capacity
I2	Current providing the maximum arc energy
I3	Minimum breaking current
I_N	Rated current
Ip	Limited cut-off current
I_{rms}	rms value of prospective current
U_{line}	Line voltage
U_N	Operating voltage between phases
Up	Breaking voltage

Design and use of MV current-limiting fuses

MV current-limiting fuses are primarily used to protect transformers, motors and other loads.

There is no need to list all the advantages which make this device so successful. Its low cost and its limiting characteristics, which significantly reduce current amplitude and the energy released in the event of a short-circuit, are among its most lauded features. There is currently no other device on the market to rival or even come close to the performance of the fuse in medium voltage (3.6 to 36 kV) applications.

However, this device does have limits which should not be exceeded. The reluctance of some users to use fuses is often due to previous bad experiences caused by a failure to follow certain basic rules of construction or use resulting in faults during operation. It is then only after carefully considering the design requirements of a fuse link that users become aware of any rules of use, which, if observed, will ensure the fuse's optimum faultless operation.

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1 Basic characteristics

1.1 Reminder

Standard IEC 60282-1 defines three current-limiting fuse categories based on the type of application in which the fuse is to be used:

Associated fuse

For applications in which the improbability of low fault current values can be proven, either by means of calculation or on the basis of past experience. However, it must be ensured that the minimum rated breaking current of the fuse link is less than the minimum short-circuit current that may appear upstream of the low-voltage safety device.

General purpose fuse

If experience or calculation indicates that there may be very low overcurrents on the line (i.e. less than approximately four times the rated current of the fuse).

Integral cut-out fuse

Recommended in particular for applications in which overcurrents may be as low as the minimum fusing current and when the fuse must be derated in order to be used in a case.

This “Cahier Technique” is concerned primarily with associated fuses, but also discusses concepts that are applicable to all fuse categories.
The basic definitions below can form the basis of a fuse dictionary that will facilitate discussions on the subject between fuse manufacturers, installation designers and users.

1.2 U_N rated voltage

This is the maximum operating voltage between phases (expressed in kV) of the line on which the fuse is to be installed.

Standardization bodies have defined a list of preferred values for rated currents. Standardized tests ensure the correct operation of a fuse with a rated voltage U_N on a line voltage U_{line} if the value of U_N, selected from this list (see **fig. 1**), is greater than U_{line}.

U_N = 3.6 - 7.2 - 12 - 17.5 - 24 - 36

***Fig. 1**: list of preferential values (kV) defined by standardization bodies.*

For reasons relating to breaking, it is not possible to use a fuse with a voltage rating U_N on a line where U_{line} is greater than U_N.
Inevitably, the reverse is sometimes possible up to values of U_N greater than that of the line. This is possible thanks to certain special design features that limit the level of the breaking overvoltage Up and enable the manufacturer (but nobody else) to ensure the fault-free operation of the fuse.
For example, on a system with a U_{line} of 10 kV, a fuse with a voltage rating of U_N = 12 kV should be selected.
If a fuse from the Fusarc-CF range is used, it is entirely possible, perhaps determined by reasons relating to standardization, to install a fuse with a voltage rating of U_N = 17.5 kV or even 24 kV.

Single-phase operation

Most fuses are designed for use on a three-phase system. In this case, the recovery voltage applied to them following a short-circuit is equal to:

$$\frac{U_{line}}{\sqrt{3}} \times 1.5$$

The coefficient 1.5 is due to the phase-shifting of the current zero points. In a three-phase system, this causes the neutral point to slip when the first fuse blows.
In single-phase operation (see **fig. 2**), a fuse with a rated voltage of U_N is therefore tested at:

$$U_N \times \frac{1.5}{\sqrt{3}} = 0.87\,U_N$$

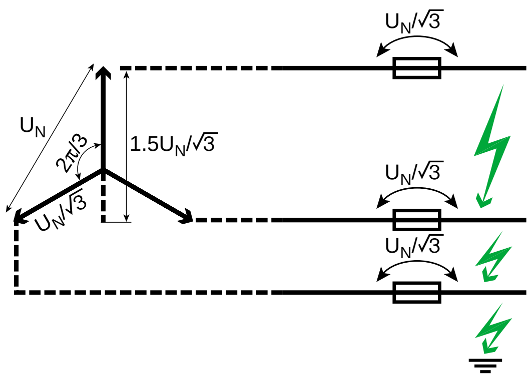


Fig. 2: voltage at the fuse assembly terminals in the event of a three-phase fault on an isolated neutral system.

In single-phase operation with a line voltage U_{line}, a fuse with the following rating should be selected:

$$U_N \geqslant \frac{U_{line}}{0.87}$$

1.3 I_N rated current

The rated current, selected from a list of preferred values, is the current which, when it flows through the fuse link installed on a given fuse base, causes temperature rises that do not exceed standardized values (these vary according to the type of material, approximately 65 K for contacts). The fuse assembly must also be able to tolerate this current permanently without sustaining any damage. In most cases, this second condition is less restrictive than the first.

It should also be noted that this purely thermal consideration changes as soon as the way in which the fuse link is installed changes. This affects fuses installed in cases and, to a lesser extent, fuse links installed on a fuse base other than the one used for the test.

A corrective coefficient appropriate for the type of installation and the fuse link must be assigned to the rated current as soon as the ambient temperature exceeds 40 °C.

1.4 I3 minimum breaking current

Current I3 is a limit value that must not be exceeded in order to ensure that a fuse will trip an electrical circuit.

Contrary to popular opinion, in the event of an MV short-circuit, the simple action of a fuse blowing will not cut off the current. For values of current less than I3, the fuse blows, but cannot break the current: the arc remains present until the current is broken by means of external intervention. Therefore, under no circumstances should a fuse assembly be used in the zone between I_N and I3. The values of I3 are generally between 2 and 6 I_N.

1.5 I2 current providing the conditions affecting maximum arc energy

This value of current, which is determined on the basis of the fusing characteristics of the fuse, results in a pre-arc time of approximately 5 ms. It enables testers and manufacturers to ensure that the current will be broken within the current range I3 to I1.

Depending on the design of the fuse elements, the value of I2 will be between 50 and 100 I_N (approximately).

1.6 I1 or maximum breaking capacity

■ This is the maximum prospective fault current that the fuse is capable of breaking. This value is the maximum value at which the fuse link has been tested.
It is therefore essential to ensure that the line short-circuit current is at least equal to current I1 of the selected fuse. The value of current I1 is very high: between 20 kA and 50 kA and in some cases even higher.

■ In the event of a short-circuit current, the fuse link will blow within several milliseconds. A peak arc voltage will appear immediately which, opposing the generator voltage and greater than it, will reduce the current value. The fuse acts like a variable resistance, which, having been almost equal to zero before the fuse blew, will increase until it reaches the current zero point, simultaneously modifying the value of the current and that of the lag between this value and the generator voltage (see **fig. 3**).

Two notions ensue from this process:

□ The maximum arc voltage Up or voltage breaking capacity, which must be minimized.

□ The current Ip, which is the instantaneous value of the short-circuit current that actually flows through the fuse assembly.

The value of Ip, which is referred to as the limited cut-off current, is often less than that of I1, which is referred to as the prospective current as it is never evident downstream of the fuse.

Up and Ip are two linked parameters, as a low Ip can be obtained easily with a high Up.

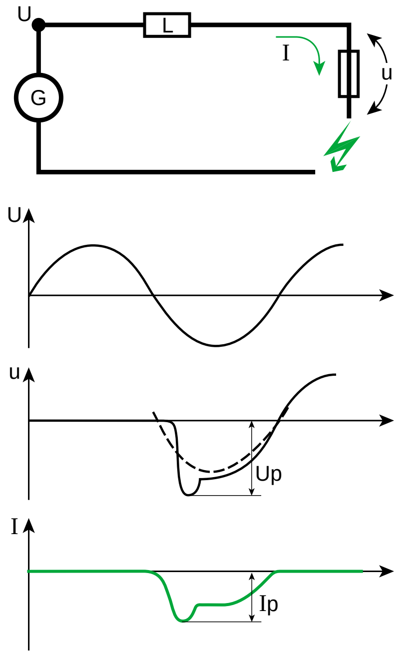


Fig. 3: diagrams showing disconnection at I1.

MV fuse design expertise is indicated by the ability of fuses to support both a low Ip (limiting stresses downstream of fuses) and a low Up (guaranteeing operation at a low U_{line} voltage before U_N).

1.7 Time/current characteristic

For each type of fuse link, there is a fusing or pre-arc duration that corresponds to an rms current value.
The duration of the pre-arc for each current value can be determined by plotting a curve on a standardized logarithmic scale (see **fig. 4**).

This curve relates only to the pre-arc. Add the arc time (typically 5 to 50 ms) to obtain the total operating time. Mention can also be made at this point to the pre-arc durations for values of current less than I3. In this case, the curve is plotted as a dotted line. It is also possible to determine the value of I3 (solid line limit) on this diagram.

This curve, which extends until it reaches a pre-arc duration of 600 s, is given with a tolerance of ± 10 % with respect to the current.

Conventionally, this curve represents a virtual pre-arc duration, which is the result of dividing the value of the integral of the energy by the

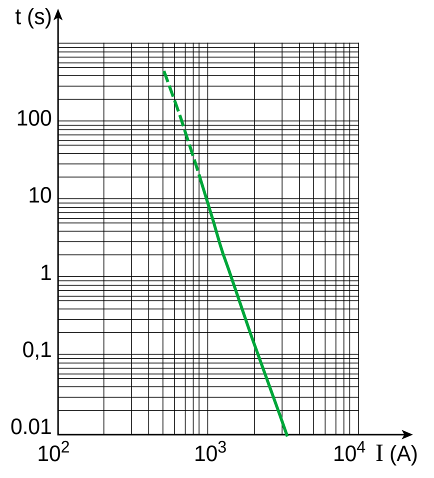


Fig. 4: pre-arc duration as a function of the rms current value.

square of the rms value of the prospective current I_{rms}.

$$t_v = \frac{\int I^2 \, dt}{\int I_{rms\ prospective}^2}$$

This duration is close to the duration of the pre-arc that would be obtained with a direct current with a value of Irms (see **fig. 5**).

Caution should be exercised when applying these charts for an alternating current. In a zone between 0 and 0.1 s, for a given current, the pre-arc durations may vary by a ratio of 1 to 3 depending on the frequency, the power factor of the circuit and the instant at which the short-circuit occurred.

By way of example, **figure 6** illustrates the actual (**a**) and virtual (**b**) pre-arc durations of a Fusarc-CF 25 A on a circuit with power factor = 0.1 for various angles of the initiation of a short-circuit of 500 A.

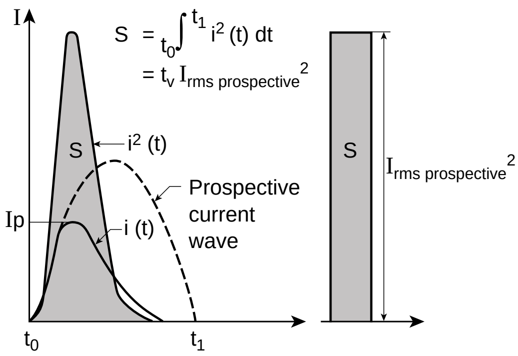


Fig. 5: chart indicating the virtual duration of the pre-arc.

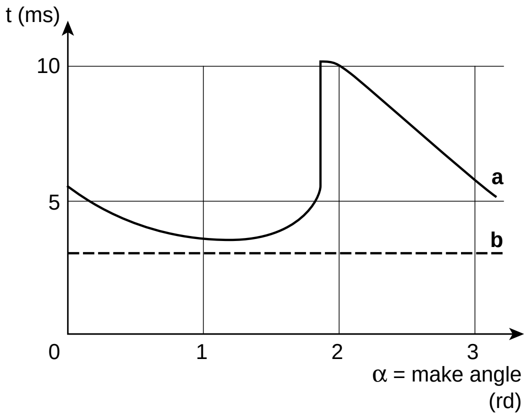


*Fig. 6: actual (**a**) and virtual (**b**) pre-arc durations on a Fusarc-CF 25 A (Merlin Gerin).*

1.8 Limited cut-off current

This current, which is an essential additional parameter for the time/current characteristic, enables the value of the limited cut-off current Ip to be determined as a function of the prospective current for current values in the region of I1 where the short-circuit current is limited (see **fig. 7**).

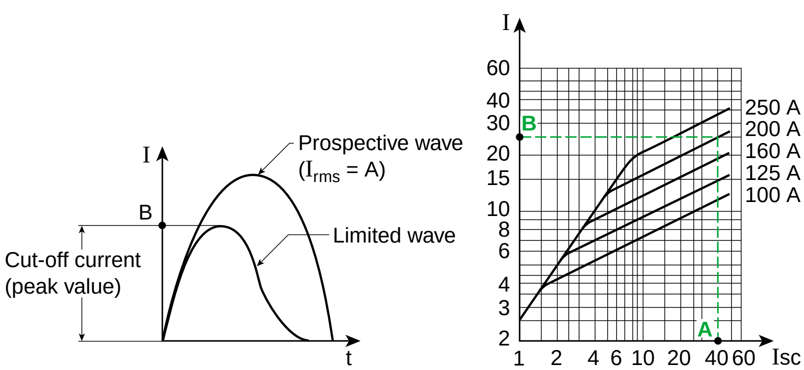


Fig. 7: value Ip of the limited cut-off current as a function of the prospective current.

1.9 Energy dissipated

In the event of a short-circuit, the amplitude of the limited current will depend on the construction characteristics of the short-circuit and the value of the integral of $\int I^2 dt$ will enable the energy dissipated in the downstream circuit to be determined as well as the calculation of its magnitude.

1.10 Power dissipated

A fuse link will dissipate a certain amount of power when carrying its rated current.

This data is often useful for dimensioning cases designed to house switchgear. Unfortunately, it is very dependent on the case itself, as well as on how the case is ventilated. In effect, the power dissipated by the fuse is determined by the resistance of the fuse links, which is in turn determined by their temperature, which depends on the cooling conditions in the case.

As well as its rated current I_N, the power dissipated by a fuse assembly is given for a specific thermal configuration.

By way of example, the power dissipated by Fusarc-CF fuses in standardized conditions (fuse link installed vertically upright) is in the region of $1.7 \times R \times I_N^2$ where:

R = cold resistance (see appendix 1).

1.7 = associated cooling coefficient. This can rise to 2 or 3 and sometimes higher for a fuse installed in a sealed case.

2 The elements of a fuse link

Based on the example of a Fusarc-CF, an examination of the various composite elements (see **fig. 8**) and the types of stress to which these elements are subject enables us to identify the possible choices available to the manufacturer.

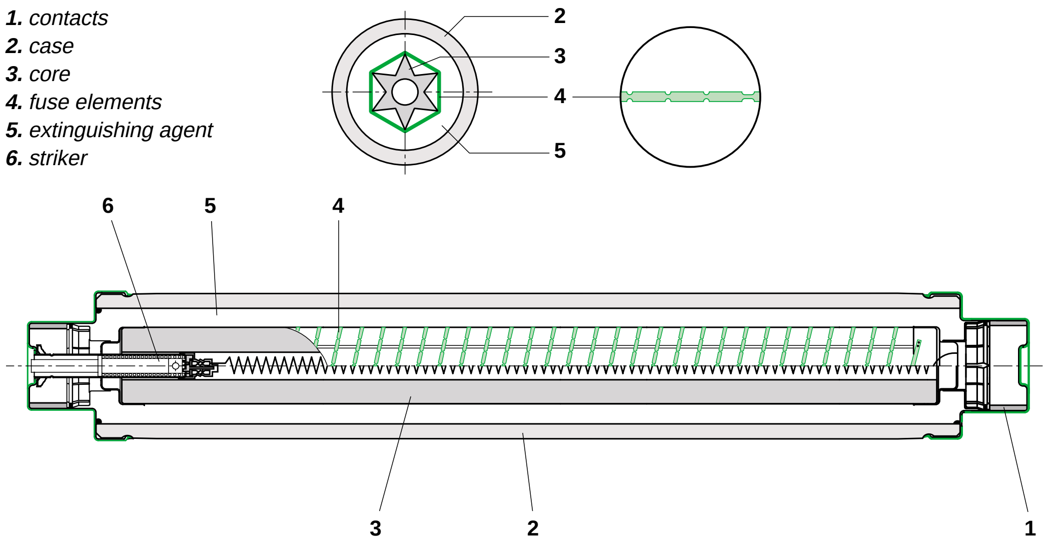


Fig. 8: sectional view of a fuse link.

2.1 End caps

End caps perform two functions:

- they act as blanking plates,
- they provide the electrical contact with the base.

Blanking plate

When connected to the case, the end caps form an assembly housing the fuse elements of the fuse assembly before, during and after the break.

This provides mechanical protection for the case, the caps and the seal between them as well as ensuring ingress protection:

- mechanical protection in the event of breaks at I1 and I2, where the significant amount of energy developed by the arc creates overpressures that may run into tens of bars,
- ingress protection, given the importance of the purity of the sand and the absence of humidity.

Contact

The end caps also ensure that the current - be it the rated current in continuous operation or the fault current - can flow between the fuse link and its fuse base.

Traditionally, in the manufacture of electrical products, the surface coatings applied to current-carrying components such as caps have been selected with a view to minimizing contact resistances, which are the primary source of overheating.

This explains the widespread use of tin and silver. Nickel is also used although it has been abandoned by many manufacturers due to its contact resistance.

The fuse assembly is a specific exception in this field. In effect, overheating is generated not by the contact but by the fuse element itself.

The family of curves in **figure 9** illustrates the contribution of the two contact resistances to the total resistance. It is clear that, for low ratings, the contribution of these resistances is extremely small. This contribution may double or even increase tenfold without affecting the thermal characteristics of the assembly.

In this case, it would seem sensible to coat the caps with nickel in order to benefit from the remarkable characteristics of this metal (anti-corrosion chemical stability) without being subject to electrical interference.

For higher ratings such as those that have to be used on more complex installations that are better protected against external influences, silver coating remains an excellent compromise.

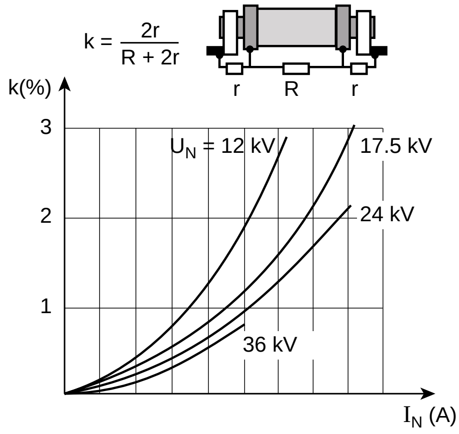


Fig. 9: contact resistances.

2.2 The tubular case

In addition to the pressure and ingress protection restrictions already mentioned, the tubular case must be able to withstand three specific types of stress: thermal, dielectric and mechanical.

Thermal stress

In addition to the stress in continuous operation at I_N, the case must be able to withstand very rapid temperature rises in the event of a break at I2 and very slow temperature rises in the event of a blow at I3.

Dielectric stress

Once the fuse has blown, the case must be able to withstand the recovery voltage. This stress, which is less severe due to the dimensions of the fuses and the lapse of time (a maximum of several hours in all but the most extreme cases) during which the voltage is applied, can be tolerated easily by all materials used.

This time lapse, which is generally very short and lasts only some tens of milliseconds when the opening of a breaking device is initiated by the fuse striker, exceeds several hours only in certain configurations. An example of such a case would be a fuse that is installed on a public supply system but is not connected to a breaking device, meaning that external intervention is required to interrupt the power supply to the two phases remaining in service.

Mechanical stress

A fuse link must offer mechanical resistance to:

■ sudden internal pressure caused by gases released in the event of a break at I2,

■ slow pressure rise caused when the sand expands in the event of a break at I3,

■ shocks to which its case may be exposed during transport and handling.

Currently, two types of case are used by manufacturers: porcelain cases and, more recently, glass-fiber-reinforced cases.

■ Porcelain offers excellent thermal and dielectric resistance. This explains why it was the initial choice of all manufacturers. Problems linked with the sensitivity of the material to shock and its fragmentation in the event of prolonged I3 fusing durations have forced some manufacturers to consider other materials.

■ Glass-fiber-reinforced resin is another example of a compromise dictated by various types of stress. Thanks to its elastic properties, its resistance to shock as well as to pressure waves is remarkable. Its thermal characteristics, which differ from those of porcelain, can also be exploited and optimized. Its dielectric strength is more than sufficient,

□ at I_N, its relative lack of depth and its thermal conductivity enable the fuse to be cooled more effectively, thereby ensuring that the fuse elements can operate at a relatively low temperature, which in turn ensures long service life,

□ above I_N, subjecting the fuse assembly to excessive stress will cause its body to darken due to the superficial oxidation of the resin caused by contact with air.

This phenomenon, which has no effect at all on the mechanical or electrical characteristics of the body, is to be viewed as a positive feature. In effect, it indicates potential faults in the installation (transformer overloaded or incorrectly adapted fuse assembly rating), in some cases enabling serious consequences to be avoided.

The criticism most frequently leveled at this type of case is its flammability. Although this was a relatively fair criticism of early versions of this material, tests have since proved its excellent performance both when exposed to heated elements at temperatures of up to 960 °C and during flame tests (IEC 60695 and ASTM D 635-68).

2.3 Core

Serving as a spindle around which the fuse element is coiled, the core simply supports the fuse. Some types of fuse do not have a core.

Made of ceramic or similar material, the nature of the core must be as similar as possible to the extinguishing agent. It is usually cylindrical in shape and ribbed (see **fig. 10**).

Often installed at its center, the striker, with its control wire, is also isolated from the fuse elements.

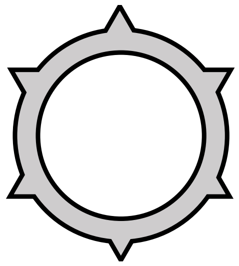


__Fig. 10__: typical sectional view of a core.

2.4 Fuse element

The fuse element is the heart of the fuse assembly.
Fuse elements can comprise wires or notched strips installed in parallel or even a single wide notched strip.

■ Wires, which were used originally, have two drawbacks:

□ they cause extremely high Up breaking overvoltages,

□ their minimum breaking currents (I3) are very high.

In fact, they are currently only used in very poor quality products (none of which are able to meet the requirements of international standards).

■ To resolve the overvoltage problem, it has been necessary to divide fuse elements into sections, thereby causing them to blow gradually. In technical terms, this is achieved by punching notches into a smooth strip.

Two I(t) characteristics shown in **figure 11** illustrate the effect of the position and depth of

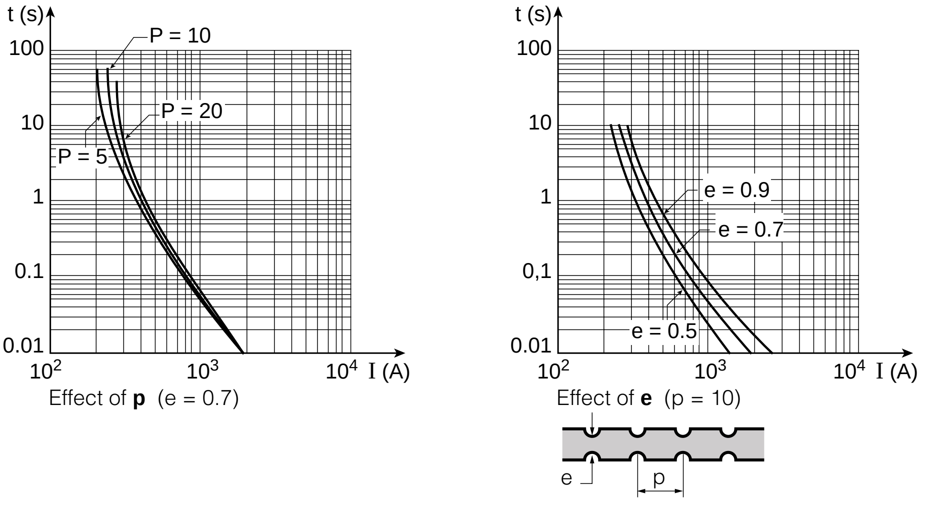


__Fig. 11__: effects of notching on a fuse element.

the notching. This characteristic can be predetermined by making a calculation based on the characteristics of the strip and the notching. Some manufacturers also use wires with sections at varying intervals (see **fig. 12**). This solution is now considered equivalent to a notched strip owing to the great similarity of the phenomena governing their operation.
This is also true of wide strips (see **fig. 12c**), which can be compared to several narrow strips that have been joined together in parallel.

Material

Silver is the preferred material for these elements.

- For a number of reasons relating to physical chemistry, silver ensures the cleanest break.

- Its low resistance, due to its relative chemical stability, makes it the ideal material for carrying an increased current without the risk of aging (operating temperature of a strip: 180 to 250 °C).

Numerous studies have been undertaken to find a less expensive alternative to silver. Few of these have proved suitable for industrial applications and it is difficult to imagine foregoing silver entirely.

Notches

Notches are of vital importance for the characteristics of a fuse. Assuming the section and length of the selected strip:

- U_N will depend on the number of notches and their depth; the more and deeper the notches, the higher the value of U_N, up to a certain limit;

- for I_N, the effect is absolutely inverted as the resistance increases;

- at I1 and I2, the depth and spacing of the notches has various effects:

  - Deeper notches will speed up fusing, leading to a more pronounced limitation effect. As a consequence, the pressure the case will have to withstand is reduced.

  - Decreasing the spacing of the notches, which enables U_N to be increased, will also increase the breaking overvoltage Us. However, this tends to reduce the duration of the arc.

- at I3, different types of notching can be applied (see **fig. 13**):

  - Notches at regular intervals enable all notches to be fused simultaneously and speed up the break. In this case, if a total length L of the notched strip is sufficient to disconnect a current I3 at a voltage U, a total length 2L of this same strip will be able to fuse twice as many notches simultaneously (doubling the peak arc voltage) and will enable the same current I3 to be disconnected on 2U.

A range in which only the length of the strip differentiates fuse links with the same I_N and different U_N will therefore have an identical I3 current for all fuses.

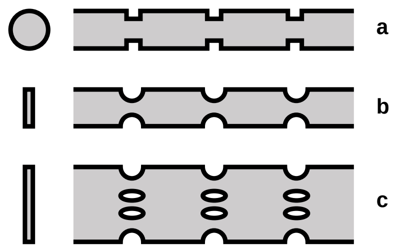


***Fig. 12**: fuse elements with sections of varying sizes.*
***a.** wire*
***b.** narrow strip*
***c.** wide strip.*

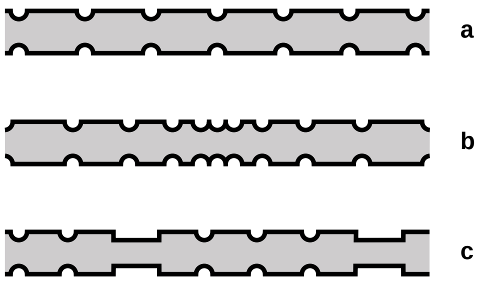


***Fig. 13**: different types of notching.*
***a.** regular*
***b.** progressive*
***c.** mixed.*

Observing this basic principle will therefore enable the U_N values of fuse assemblies to be increased (36, even 72 kV) while maintaining a low I3 value.

  - A central zone with a considerably higher number of notches than the rest of the element localizes the fusing and the length (i.e. the voltage) of the arc increases gradually until the circuit breaks.
If the duration of the arc becomes too long, the increase in the peak arc voltage due to the elongation of the arc is compensated by the decrease in the arc voltage in the middle of the strip (zone where the arc has developed to its full potential) and by the magnification of the arc channel. At this point, this disconnection method reaches its limit.
By applying this principle, a very low I3 can be achieved easily for U_N values of 3.6 and 7.2 kV, but this increases significantly once U_N exceeds 12 kV, and the maximum value of U_N in this type of range never exceeds 24 kV.

  - A mixed system by means of which certain manufacturers have been able to achieve optimum results.

Schneider Electric has retained the notched strip technique, as its cooling characteristics, which are better than those of a wire, enable the value of the minimum breaking current I3 to be reduced.

2.5 Extinguishing agent

This is usually sand (quartzite), which, by vitrifying, absorbs the high levels of energy developed by the arc and combines with the silver to form an insulating compound known as "fulgurite". Its purity is essential to ensure reliable breaking in all areas, as is the absence of metallic compounds and humidity.

Furthermore, its initial bulk ensures that the pressure (and therefore the voltage) of the arc channel is maintained.

Its granularity is selected according to the following data, which has been drawn from experience:

- too fine a granularity (< 20 µ) is very detrimental as its high density, which slows down the diffusion of the fuse metal between the grains of sand, makes the gradual elongation and subsequent extinction of the arc difficult;
- fine granularity facilitates breaks at $I1$ and $I2$ but also favors overvoltages;
- coarse granularity enables $I3$ to be reduced. Modifying the granularity also enables the time/ current characteristic in the zone 10 ms, 500 ms to be made more concave.

2.6 Striker

This is a mechanical component that indicates that the fuse assembly has blown and is able to supply a certain amount of energy stored in a spring in order to activate a breaking device. Fuses with strikers are therefore designed for fuse combination units.

The striker actuator is always a resistive wire (tungsten, Ni-Cr, etc.) installed in parallel to the fuse elements. At I_N, an extremely low current flows through it. However, as soon as an overcurrent flows through the fuse assembly, this current increases significantly until it melts the wire and releases the spring-loaded striker. Extreme care should be taken when designing the wires, as they must not cause premature tripping but must ensure tripping without interfering with the breaking process.

Striker types are classified in several standardized categories (low, medium and high) according to the energy they are capable of supplying.

Dangerous temperatures (> 100°C on the contacts) for a breaking device combined with fuses and/or fuses themselves can be invoked by prolonged overcurrents. To suppress this risk, recent developments have enabled a thermal trip to be incorporated into a traditional (spring-loaded - medium type) striker system (see **fig. 14**).

This trip also acts on the striker, which invokes the opening of the device.

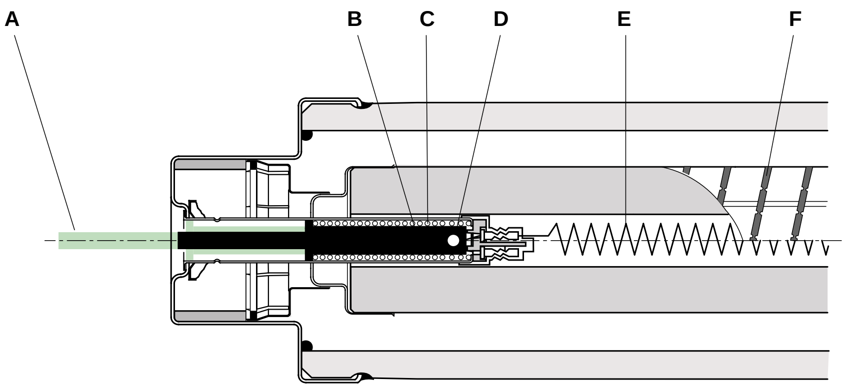


***Fig. 14**: example of a thermal trip unit incorporated into the striker system of all Merlin Gerin brand fuses.*
***A.** striker released*
***B.** striker in normal untripped position*
***C.** spring*
***D.** thermal trip for striker*
***E.** electrical trip for striker*
***F.** main fuse element.*

3 Application

This section discusses the regulations determining the selection of the rating of the fuse link for a fuse used in good ventilation conditions. These rules can be used to draw up usage tables for fuse ranges.

When connected to or combined with a connecting device, the fuse can also be used to protect various loads, in particular transformers, motors and capacitors. In these assemblies, the fuse and the connecting device must be matched and, in addition to the ventilation conditions, manufacturer recommendations for the combined or associated unit must be taken into account when selecting the rating of the fuse link.

3.1 General

The regulations to be observed for U_N and I1 were discussed in the first section. These characteristics, which are specific to the fuse, must be greater than or equal to the line voltage U_{line} and its short-circuit current Isc. These basic considerations determine the characteristics of the installation and in some cases exclude the use of certain types of fuse.

However, other regulations associated with the specific characteristics of the protected load must also be observed. These are addressed in subsequent sub-sections, in which the regulations are given for fuses with standard ventilation. If the fuses are housed inside cases with very poor ventilation, in addition to the regulations below, it must also be ensured that any temperature rises during continuous operation do not exceed standardized values. If necessary, the fuse links should be derated.

3.2 Protecting transformers

Standard IEC 60787 deals specifically with fuses designed for this type of application. This type of load imposes three major restrictions on the fuse link:

- it must be able to withstand the voltage peak that occurs when the load is switched on without blowing inappropriately,
- it must be able to withstand the continuous operation current and any overloads,
- it must be able to cut off fault currents at the transformer output terminals.

Energization peak

When a transformer is powered up, the degree of instability will depend on the instant at which the voltage is applied and the remanent induction of the magnetic circuit.

The asymmetry and the current are maximized if the transformer is switched on at a voltage zero point and if the remanent induction on the same phase is at maximum.

Figure 15 illustrates the progress of the steady state current.

In order to select the fuse assembly, you must know the rms value of the inrush current and its duration.

The rms value of the transient state current is calculated using the following equation:

$$I_{rms}^{2} = 0.125\, I_C^{2}\, \frac{\tau_a}{t}\left(1 - e^{-\frac{2t}{\tau_a}}\right)$$

where:

I_C = maximum peak current

τ_a = time constant for current damping in seconds (time at the end of which the current will have fallen to 37 % of its initial value).

t = time (in seconds) at the end of which it is estimated that the current will have reached its normal operating value

Usually, t = 3 τ_a.

The table in **figure 16** contains standard values for I_C/I_N and τ_a depending on the power rating of the transformers for devices meeting the requirements of standards UTE C 52-100, C 52-112 and C 52-113.

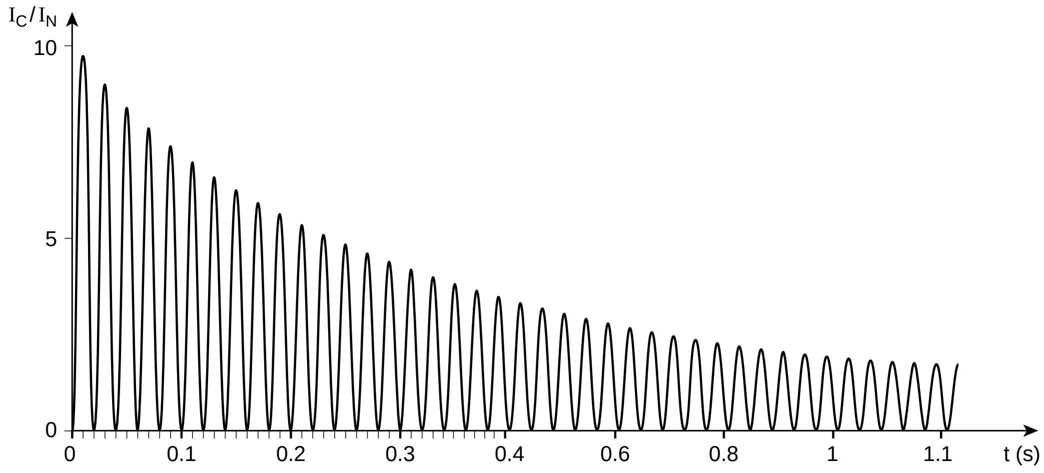


Fig. 15: maximum inrush or peak current of a 1 000 kVA transformer.

P (kVA)	I_C / I_N	τ_a (s)
50	15	0.1
100	14	0.15
160	12	0.20
400	12	0.25
630	11	0.30
800	10	0.30
1 000	10	0.35
1 250	9	0.35
1 600	9	0.40
2 000	8	0.45

Fig. 16: ratio of the maximum peak current to the rated current of the transformer and values of τ_a.

A simple technique that has been proven in practice and takes into account these stresses while preventing the fuse from aging due to the reappearance of such stresses is to always check that the current that causes the fuse to blow in 0.1 s is always greater than or equal to 12 times the current I_N of the transformer.

Steady state and overload mode

In order to avoid premature aging of the fuse elements and taking into account in-cell installation (increased ambient air temperature), the minimum rating of the fuse must be greater than or equal to 1.4 times the I_N of the transformer.

A rating of this nature is worthwhile in normal temperature conditions as defined by IEC recommendations, i.e. an ambient air temperature not exceeding + 40 °C and a measured average over a period of 24 hours at + 35 °C maximum.

If the transformer has been designed to operate with permanent overload, this must be taken into account when selecting the rating of the fuse assembly. The following rule should be applied:

1.4 $I_{overload} \leqslant$ rating of fuse assembly.

Fault current at the transformer output

In all cases, it must be ensured that the current to be broken is greater than or equal to I3, the minimum breaking current of the fuse. If a protection relay has not been provided on the MV side for detecting short-circuits at the output (LV side) of the transformer being protected, this function must be performed by the fuse.

The value of the secondary short-circuit current in relation to the primary current will be:

Transformer I_N / Usc %,

where Usc % = short-circuit voltage (in %)

The rule is:

I_N / Usc % $\geqslant$ I3

The following three rules:

- I fuse (0.1 s) > 12 times the transformer I_N,
- 1.4 $I_{overload}$ < fuse assembly rating,
- I_N / Usc % > I3,

can be used to define the range of I_N values a given fuse is able to protect.

The table in **figure 17** clearly shows that there is no direct relationship between the rated current and the operating current. Many users, to whom neither the fuse nor the rated current are known, are unaware of this phenomenon. In practice, the rated current can be ignored and the fuse link can be characterized simply by its IA and IB threshold values, provided that the user is aware that the IA limit may be exceeded if a suitable protection relay is used.

Rating (A)	I_{min} fuse (A) 0.1 s	$I_{N\ max.}$ = $I_{min(0.1)}$ / 12	$I_{N\ max.}$ = I_N fuse / 1.4	I3	$I_{N\ min}$ = I3 x 5%	Transformer I_N must be between IA	and IB
4	14.3	1.1	2.8	20	1	1	1.1
6.3	29.9	2.4	4.5	36	1.8	1.8	2.4
10	59.2	4.9	7.1	34	1.7	1.7	4.9
16	84.7	7	11.4	46	2.3	2.3	7
20	103.8	8.6	14.2	55	2.7	2.7	8.6
25	155.5	12.9	17.8	79	3.9	3.9	12.9
31.5	207.5	17.2	22.5	101	5	5	17.2
40	278.5	23.2	28.5	135	6.7	6.7	23.2
50	401.7	33.4	35.7	180	9	9	33.4
50 (36 kV)	385	32	35.7	200	10	10	32
63	499.8	41.6	45	215	10.7	10.7	41.6
63 (36 kV)	489.6	40.8	45	250	12.5	12.5	40.8
80 (7.2-12 kV)	680	56.6	57.1	280	14	14	56.6
80 (17.5-24 kV)	694.6	57.8	57.1	330	16.5	16.5	57.1
100 (7.2-12 kV)	862	71.8	71.4	380	19	19	71.4
100 (17.5-24 kV)	862	71.8	71.4	450	22.5	22.5	71.4
125	1 666.1	138.8	89.2	650	32.5	32.5	89.2
160	2 453.4	204.4	114.2	1 000	50	50	114.8
200	3 256.3	271.3	142.8	1 400	70	70	142.8
250 (3.6 kV)	4 942.4	411.8	178.5	2 000	100	100	178.5
250 (7.2 kV)	4 942.4	411.8	178.5	2 200	110	110	178.5

Fig. 17: table summarizing the possibilities of the Fusarc-CF (Merlin Gerin) range, with a short-circuit voltage of 5 %.

3.3 Motor protection

The fuse can be combined with a contactor to create a safety device that is particularly effective for an MV motor.

The specific types of stress that fuses for protecting motors must be able to withstand are imposed by the motor itself or by the specific features of the system on which the motor has been installed. A specification for this type of use (IEC 60644) has been developed in addition to the generic standard for MV current-limiting fuses (IEC 60282–1).

Motor-induced stress

■ During startup

The load characteristic for an MV motor is illustrated in **figure 18**. This characteristic shows that, when a motor is being powered up and throughout the starting phase, its impedance is such that it draws a current I_S that is clearly greater than the rated load current I_N.

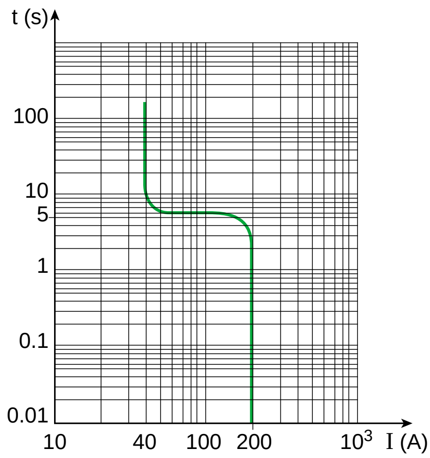


Fig. 18: load diagram for an MV motor.

This current, I_S, which is known as the starting current or the locked rotor current, is quantified by the ratio I_S/I_N, which is typically equal to 6 in the case of direct on-line starting.

The starting time, t_S, which lasts for approximately ten seconds, depends on the type of load being driven by the motor.

In addition to the permanent rated current of the motor, which is relatively high, the fuse must be able to withstand this current peak repeatedly without blowing inappropriately. The possibility of several successive starts must also be taken into account.

■ Overload

A motor is always protected by an interlock circuit, which, in the event of an excessive overload, will send an opening instruction to the relevant breaking device. This means that the fuse is never required to disconnect low currents and the value of its current (I3) is of little importance.

Line-induced stress

■ Rated voltage

The maximum rated voltage of MV motors does not usually exceed 11 kV. Therefore, only fuses with ratings of $U_N \leqslant 12$ kV are affected.

■ Limited cut-off current

MV motors usually operate on high-performance industrial systems. The short-circuit current is therefore also very high (50 kA for example).

In addition, the motors are frequently supplied with power by very long cables.

Their size is determined not only by the rated current but also by the short-circuit current that may flow through them.
Increased limitation (low Ip) is therefore advisable and should be given careful consideration.

Configuring the fuse link

Here also, the fuse to be selected is determined on the basis of the time/current characteristic. The use of charts enables the most appropriate fuse link to be selected directly.

■ Using charts

The chart in **figure 19**, used for the direct selection of a Fusarc-CF element, has three families of curves.

□ Family **I** shows the rated current of the motor as a function both of its power in kW (1 CV =0.7 kW) and of its rated voltage.

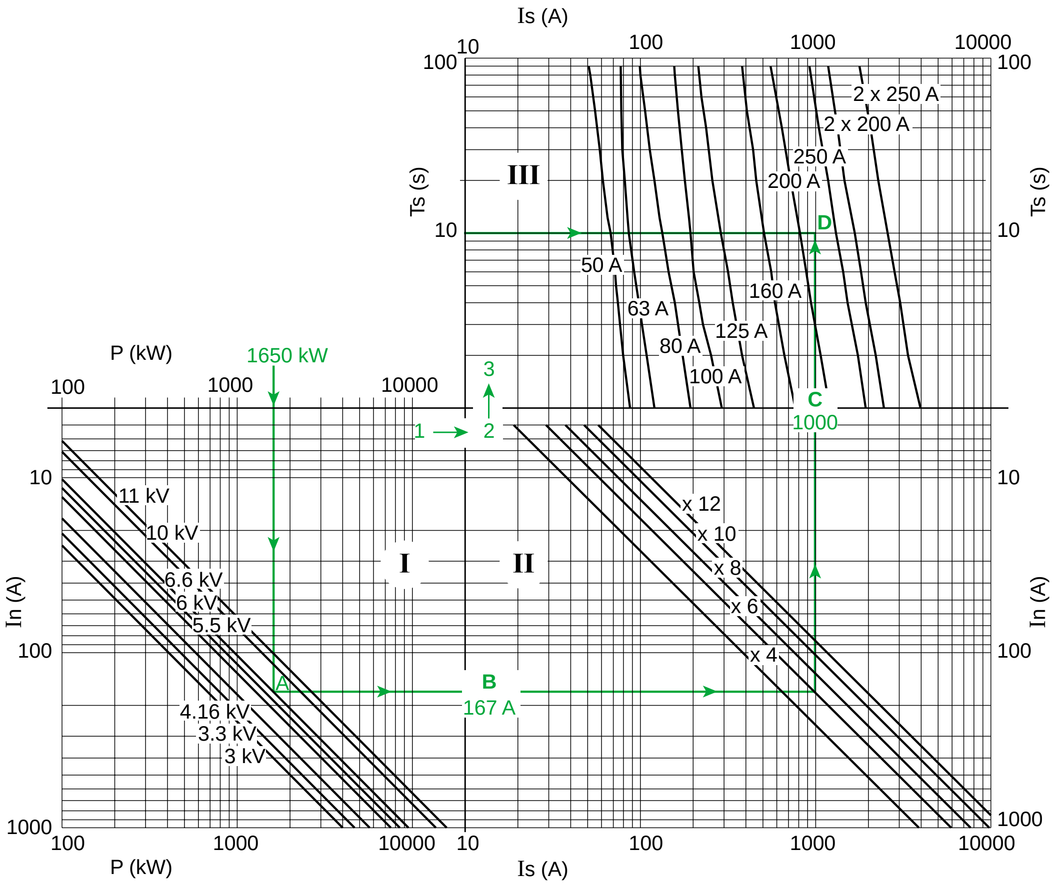


Fig. 19: chart illustrating the time/current characteristics of fuses in the Fusarc-CF (source Merlin-Gerin) range.

The efficiency η and the power factor when the motor is started up are assumed to be in the region of:

η x cos φ = 0.86.

Once the exact values are known, I_N can be determined by the following formula:

$$I_N = \frac{P\,(kW)}{U_N\,(kV) \times \sqrt{3} \times \eta \times \cos\varphi}$$

□ Family **II** shows the starting current based on the rated current and according to the ratio I_S / I_N.
In the absence of other information, use $I_S / I_N = 6$.

□ Family **III** enables the rating of the fuse link to be determined directly based on the duration of the motor startup phase (t_S) and the starting current (I_S) for 6 starts within one hour or 2 consecutive starts.
In the absence of other information, use $t_S = 10$ s.

■ Practical example (see fig. 19)

A motor with a rating of 1650 kW, 16.6 kV (point **A**) has an I_N of 167 A (point **B**).
If $I_S / I_N = 6$, the value of I_S will be 1000 A (point **C**).
If $t_S = 10$ s, the result (point **D**) lies between the curves for ratings 200 A and 250 A. The fuse link must therefore have a rating of 250 A.
The startup time must be calculated for the following three cases:

□ for **n** starts within one hour, if n ⩾ 6: multiply t_S by n / 6;

□ for **p** consecutive starts, if p ⩾ 2: multiply t_S by p / 2;

□ for **n** non-consecutive starts (where n ⩾ 6) and p consecutive starts (where p ⩾ 2): multiply t_S by n / 6 and by p / 2.

If the motor is not started directly on-line, the rating calculated using the charts may be less than the full load current of the motor. If this is the case, a rating greater than this current must be selected.

In every case, the fuse link must be taken into account and derated depending on the ventilation in the cell (example: use a coefficient of 1.2 for a link with standard ventilation).

Using these charts correctly will ensure conformance to aging tests for fuses according to standard IEC 60644.

■ Without chart

The appropriateness of a fuse for a motor can still be verified even without a chart. To do this, simply calculate the starting current and time values of the motor. A point (t_S, K I_S) can be identified by applying a multiplication factor K, which will vary between 1.8 and 2 depending on the manufacturer. This point, when recorded on the time/current characteristic, must be located to the left of the curve for the fuse link to be selected.

Factor K compensates for a number of types of stress, among them multiple starts including starts with fuses that are still warm from the previous cycle.

3.4 Protecting capacitor banks

Stress specific to the protection of capacitor banks by fuses, which is addressed in IEC 60549, can be divided into two types:

■ stress during bank energization: the inrush current, which is very high, can cause the fuses to age or blow,

■ stress during operation: the presence of harmonics may lead to excessive temperature rises.

The types of stress also vary depending on the type of configuration: single bank or multiple step bank.

Temperature rise

If capacitors are used, because of the harmonics, which cause additional temperature rise, a common rule for all equipment is to derate the rated current by a factor of 30 to 40 %.

This rule applies equally to fuses, which, when combined with the derating required to take into account their installation, results in a coefficient of 1.7 to be applied to the capacitive current in order to determine the appropriate fuse link rating.

Inrush current peak

■ Single capacitor bank

This type of circuit can be illustrated as shown in the diagram in **figure 20**, in which:

L = generator inductance

R1 = fuse resistance (see appendix 1)

R2 = resistance of the upstream circuit, calculated based on U_N, Isc and cos φ.

When starter D closes, the transient current I_T of the load C is applied, where R = R1 + R2, according to the equation:

$$I_T = \frac{V}{L\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}}\, e^{-\frac{R}{2L}t} \times \sin\left(\sqrt{\frac{1}{LC} - \frac{R^2}{4L^2}}\; t\right)$$

V is the voltage in **A** on closing.
The orders of magnitude of L, R and C mean that the following terms can be ignored: $\frac{R^2}{4L^2}$

on the basis of which:

$$I_T = V\sqrt{\frac{C}{L}} \times e^{-\left(\frac{Rt}{2L}\right)} \times \sin\frac{t}{\sqrt{L}}$$

This transient current is superimposed onto the 50 Hz wave, which results in the current wave form illustrated in **figure 21**.

The current is at maximum value when V reaches the voltage peak, i.e.:

$$V = U \times \frac{\sqrt{2}}{\sqrt{3}}$$

As with transformers, the fuse selection can be validated by checking the relationships between the peak current and the rated current I_T / I_N as well as the rise time constant.
Therefore, if:

$$U_N = \frac{U \times C\omega}{\sqrt{3}},$$

the I_T / I_N ratio can be expressed as:

$$I_T / I_N = U \times \sqrt{\frac{2C}{3L}} \times \frac{\sqrt{3}}{UC\omega} = \frac{1}{\omega}\sqrt{\frac{2}{LC}}$$

$$\text{and } \tau_T = \frac{2L}{R}$$

Experience has shown that it is absolutely vital that the fuse does not blow for a current I_T during time t_T.

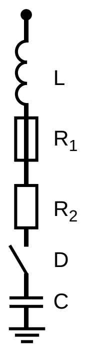


Fig. 20: diagram of a single capacitor bank.

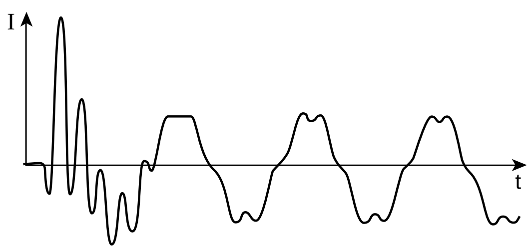


Fig. 21: transient current wave on starting a capacitor bank.

If this restriction is not imposed, the higher rating must be used and I_T and τ_T must be recalculated in order to repeat the verification process.

■ Practical example for a single capacitor bank
U_N = 10 kV
I_N bank = 35 A
Isc = 40 kA (cos φ = 0.1)
C = 19.3 x 10^{-6} F
By means of the calculation:
L = 0.46 x 10^{-3} H
R2 = 14.5 x 10^{-3} Ω.
The rating calculated on the basis of the thermal criteria is:
35 x 1.7 = 60 A
This results in the selection of the following standard rating:
I_N fuse = 63 A.

In appendix 1,
R1 = 13 x 10^{-3} Ω for a fuse rated at 63 A/12 kV
or R = 27.5 x 10^{-3} Ω
on the basis of which I_T = 1670 A and
τ_T = 33.5 x 10^{-3} s.

A comparison with the time/current characteristics (appendix 2, point **A**) shows that a rating of 125 A must be selected.
Therefore, R1 = 5 x 10^{-3} Ω and R = 19.5 x 10^{-3} Ω, on the basis of which I_T = 1670 A and
τ_T = 47.2 x 10^{-3} s.
When recorded on the curves for point (**B**), this point confirms that a rating of 125 A is indeed correct.

■ Multiple step capacitor bank (diagram in **figure 22**).

When the bank in position n is switched on, supposing that the (n-1) other banks have already been switched on, the oscillatory load will be identical. However, in this case, the other

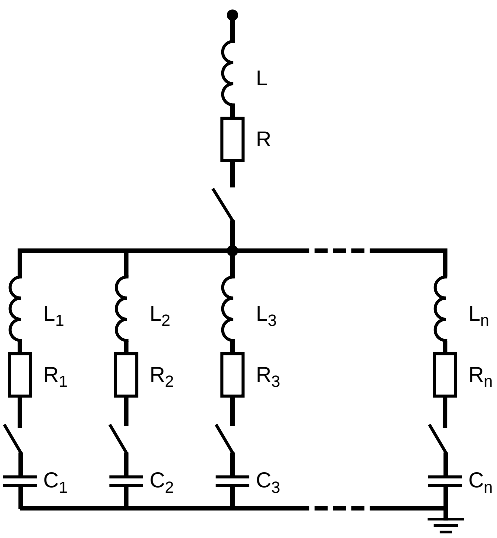


Fig. 22: diagram of a multiple step capacitor bank.

banks connected in parallel will act as additional sources of very low internal impedance. This internal impedance (inductance Li in fig. 22) comprises stray inductances from busbars and cables (order of magnitude 0.4 µH/meter) and may also comprise an interference suppressor choke designed to limit the inrush current. In effect, this current not only poses a danger to the fuse elements, it also compromises the electrical endurance of the switchgear and may even compromise the service life of the capacitors themselves.

As the inrush current flowing via L may be negligible, the inrush current is calculated by applying the following formula:

$$I = U\sqrt{\frac{2}{3} \times \frac{C_E}{L_E}} \times e^{-\frac{R_E t}{2L_E}} \times \sin\frac{t}{\sqrt{C_E \times L_E}}$$

where

$$C_E = \frac{Cn\ Cs}{Cn + Cs} \quad \text{where} \quad Cs = \sum_{i=1}^{n-1} Ci$$

$$L_E = Ln + Ls \quad \text{where} \quad Ls = \frac{1}{\sum_{i=1}^{n-1} \frac{1}{Li}}$$

$$R_E = R + Rs \quad \text{where} \quad Rs = \frac{1}{\sum_{i=1}^{n-1} \frac{1}{Ri}}$$

Although appearing to be similar to the calculation for the single bank, this calculation is in fact slightly more complicated.

You must:

□ select a fuse link according to the thermal criteria

□ calculate $I_T = U\sqrt{\frac{2}{3} \times \frac{C_E}{L_E}}$

□ calculate $\tau_T = 2 \times \frac{L_E}{C_E}$

□ record the point (I_T, τ_T) on the time/current characteristics,

□ if necessary, select a different rating, calculate a new R_E value and start the verification process again.

If the steps are identical, a single calculation will suffice. However, if they are not, you must investigate several scenarios according to the operating mode of the bank.

■ Practical example for a multiple step capacitor bank

3 banks:

U_N = 10 kV

I_N bank = 35 A

Isc = 40 kA (cos φ = 0.1)

Cables = 5 rn or Li = 2 µH

When the third step closes:

Ci = 19.3 x 10^{-6} F and Ls = 1 µH

Ri = 5 x 10^{-3} Ω and Rs = 2.5 x 10^{-3} Ω

On the basis of which:

C_E = 12.9 µF

L_E = 3 x 10^{-6} H

R_E = 7.5 x 10^{-3} Ω

I_T = 16900 A

τ_T = 0.8 x 10^{-3} s.

The time/current characteristics do not provide specific data for pre-arc durations of less than a millisecond. A value of I^2 x t constant can be estimated in this zone. If the minimum value of the fuse assembly is assumed to be 125 A (defined in the previous example), this results in the following values:

I_N fuse	I^2 t fusing
125 A	64 x 10^3 A^2 s
160 A	76 x 10^3 A^2 s
200 A	140 x 10^3 A^2 s

The stress applied to the fuse assembly rated at 125 A is:

0.8 x 10^{-3} x $(16900)^2$ = 228 x 10^3 A^2 s

and even 200 A is unsuitable.

This type of bank cannot be protected in this way using Fusarc-CF fuses.

In some impossible cases, there is a solution that consists of protecting all three banks with a single common fuse (see **fig. 23**).

With this type of diagram, two cases should be considered:

□ the three banks cannot be powered up simultaneously.

In this case, each time a bank is powered up, the fuse interprets this as the activation of a single

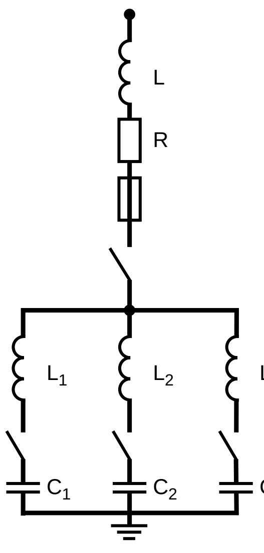


***Fig. 23**: diagram of a bank with three capacitor steps protected by a single fuse.*

bank. A fuse with a rating of 125 A can withstand the inrush current (see the example above).

The main type of stress is thermal stress, which imposes a rated current of

3 x 35 x 1.7 = 179 A or I_N fuse = 200 A.

□ all three banks can be powered up simultaneously.

The system becomes equivalent to a single bank with triple power, i.e.:

L = 0.46 x 10^{-3} H

C = 57.9 x 10^{-6} F

I_T = 2 900 A

Assuming a fuse with a rating of 200 A, (R1 = 2.5 x 10^{-3} Ω) where R2 = 14.5 x 10^{-3} Ω (see above) τ_T = 54 x 10^{-3} s

Point C, appendix 2, shows that 200 A is suitable in the majority of cases.

Paradoxically, in this case, it is possible to protect all three banks globally using one fuse despite the fact that protecting each individually is impossible.

3.5 Summary

The table in **figure 24** contains a summary of the requirements of the different types of fuse according to the type of load.

These specifications can be used to plot the ideal time/current characteristic for a fuse according to its use (see **fig. 25**).

This diagram clearly shows the contradictory requirements of each type of load protected. It also clearly illustrates the relative insignificance of the I_N value of a fuse when it is taken alone as a selection criterion (as is unfortunately too often the case).

Type of load	Transformer	Motor	Capacitors	
			Single bank	**Multiple step banks**
Order of magnitude of fuse rating	4 to 100 A	100 to 250 A	100 to 250 A	
Selection rules	$I_A < I_N$ transf.< I_B	Fixed by Ip and t_D I_N motor x 1.2	I_N bank x 1.7 < I_N fuse In_{sc} fixed by î, t	
Ip	No specification	Low		High τ ≈ 1 ms
I fusing 0.1 s	High	No specification	High (τ ≈ 0.1 s)	No specification
I fusing 10 s	Low for close-up protection	High	Low for close-up protection	
I3		No specification		
U_N	0 to 36 kV	0 to 12 kV	0 to 36 kV	

Fig. 24: types of fuse according to the loads to be protected.

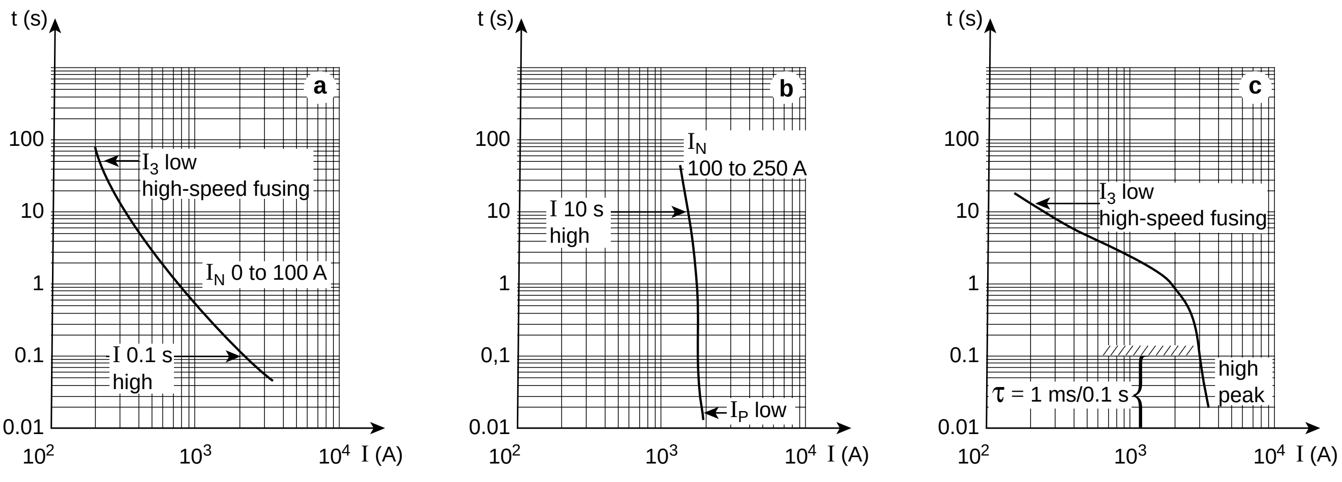


Fig. 25: ideal time/current characteristics for protecting:
a/ a transformer,
b/ a motor,
c/ a capacitor.

■ For transformers

It is likely that developments in standards designed to standardize time/current characteristics will in the future enable users to forego selection rules for transformers and consider only the rated current of the transformer when making their selections.
Until then, a step in the right direction would be for every manufacturer to provide the operating limits IA and IB for the fuse links they produce.

■ For motors

Unfortunately, this is an entirely different case, as the rating of the load is not the only characteristic required in order to select an appropriate fuse link.
Although standards set out criteria to be observed and require precise indications from manufacturers (K factor, time/current characteristic), users still have to select fuses themselves on the basis of the motor to be protected, with the assistance of aids (charts, tables) provided by fuse manufacturers.

■ For capacitors

It has been shown that it is even more difficult to select fuses for capacitors as the system geometry and fuse characteristics have to be taken into account. It is very difficult to be sure of the appropriateness of a selection in technical terms without knowing the resistance of the fuse.

In conclusion

The use of MV current-limiting fuses presupposes extensive product knowledge. This is why users must refer to the necessary information provided by manufacturers such as Schneider Electric.

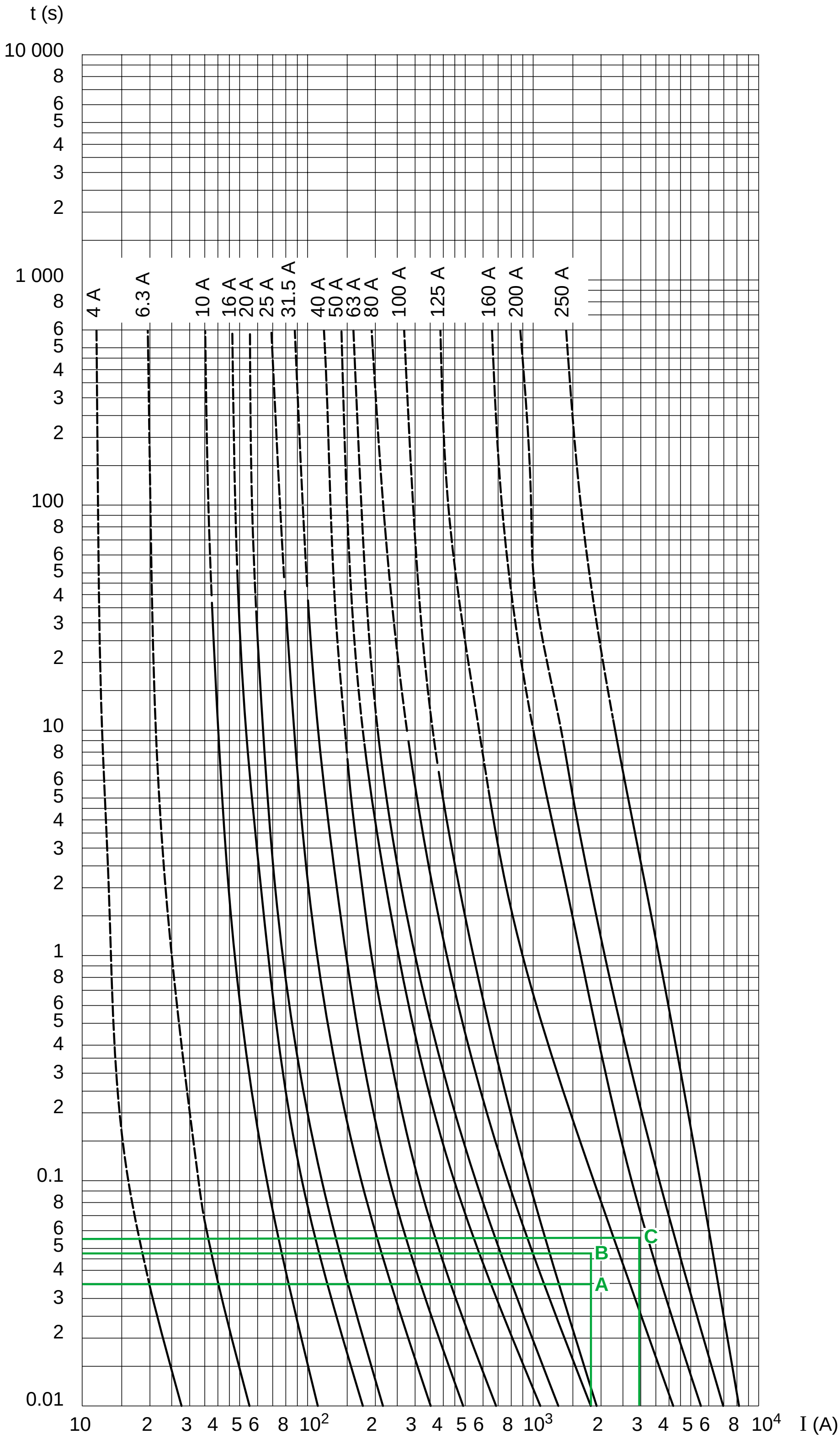
Equally, when designing a range of fuses, manufacturers must consider the types of stress to which each different fuse link will be subject. This is an exercise that was undertaken for example when the different products in the Fusarc-CF range were being developed: ratings were assigned to groups according to the types of stress illustrated in figure 25. Fuses up to 125 A are "transformer" or "capacitor" type fuses and fuses with higher ratings are more suitable for protecting motors. Thus, a single range is able to meet almost all requirements and provide optimized protection for loads.

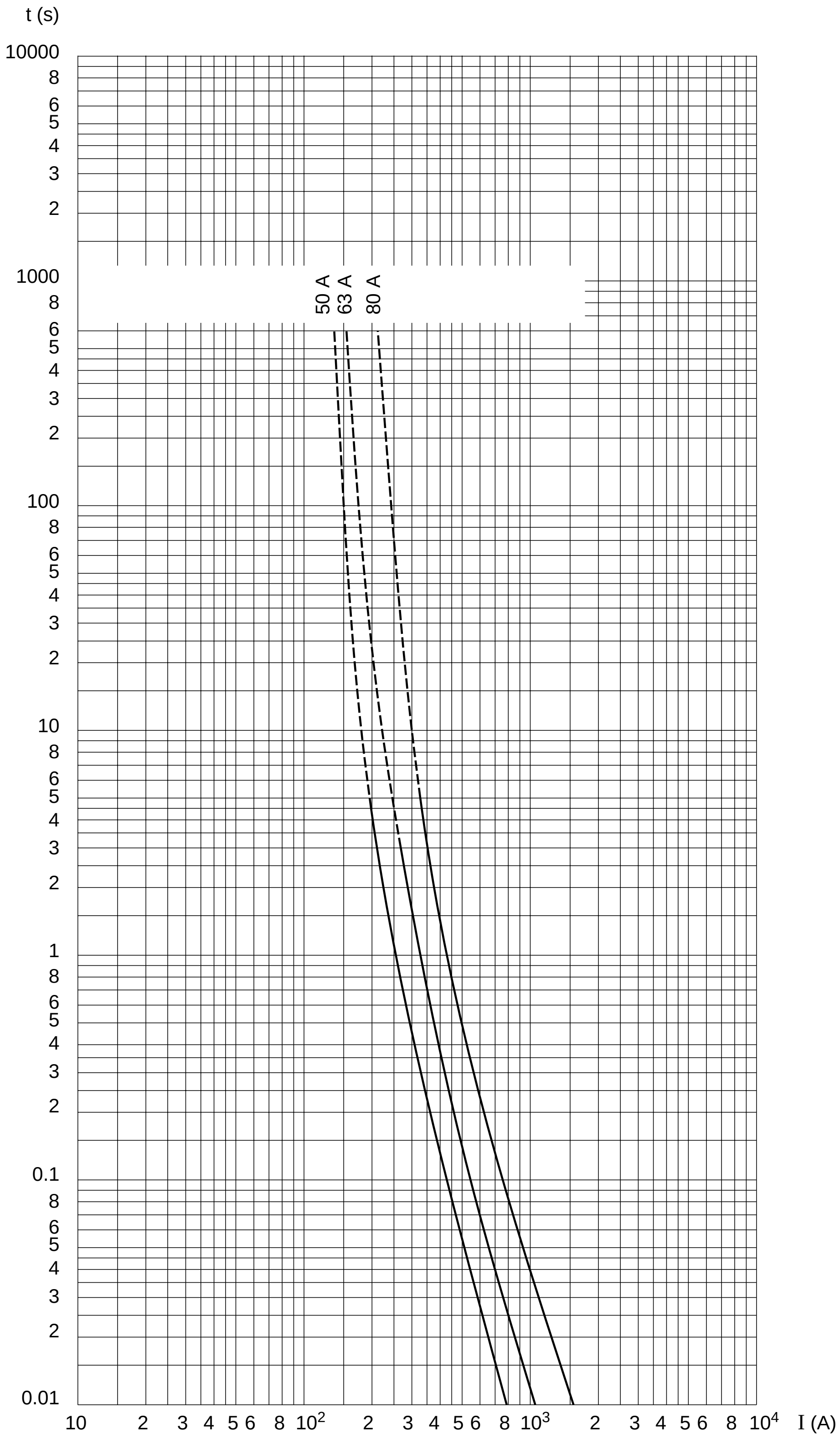
4 Appendices

4.1 Appendix 1: Cold resistance of Fusarc–CF fuses

Rating	3.6 kV	7.2 kV	12 kV	17.5 kV	24 kV	36 kV
4 A		762	1 143	1 436	1 436	2 109
6.3 A		205	319	402	485	750
10 A		102	158	203	248	380
16 A		68.5	106	132	158	252
20 A		53.5	82	103	123	197
25 A		36.4	56	71	85	133
31.5 A		26	40	51	61	103
40 A		18	28	35	42	70
50 A		11.7	17.4	22	31.5	47
63 A		8.4	13.8	19.4	23.6	35
80 A		6.4	10	13.5	18	
100 A		5.5	8	11	13.5	
125 A		3.4	5.3			
160 A		2.2	3.5			
200 A		1.8	2.7			
250 A	0.6	0.9				

4.2 Appendix 2: Time/current characteristics in the Fusarc–CF range of fuses (Merlin Gerin)




t (s)
10000
1000
100
10
1
0.1
0.01
50 A
63 A
80 A
10
10^2
10^3
10^4
I (A)

4.3 Appendix 3: Using fuses in parallel

■ The problem

In some extreme cases, two or three fuse links have to be installed in parallel.

It is therefore essential to ensure as ideal a symmetry as possible in order to prevent secondary effects compromising the equal distribution of the current between the two links.

If possible, in order to avoid disparities between links, it is advisable to install a source of impedance (a cable for example) between each link, with a rated value that is greater than that of the fuse assembly.

Another technique is to use two current transformers (precision is relatively unimportant as they are not used for the purposes of measurement) whose outputs should be connected in series according to the diagram in **figure 26**.

Current balancing is also ensured at I_N.
However, it cannot be ensured at higher current values due to transformer saturation.
In all cases, this type of installation is only possible with fuse links of equal ratings and is subject to manufacturer approval.

■ Electrical characteristics of an assembly comprising n identical fuse links installed in parallel.

□ U_N: the rated voltage U_N of the assembly is the voltage of each of the component links.

□ I_N: in theory, the rated current I_N of the assembly is the rated current of the component links multiplied by n. In practice, taking account of the proximity of the links and imperfections in current distribution, the rated current of the assembly is derated by 20 %. For example, an assembly comprising two parallel links rated at 200 A will have an I_N of: 2 x 200 x 0.8 = 320 A.

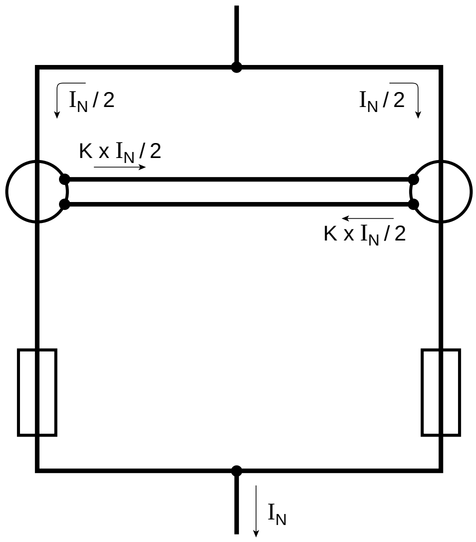


***Fig. 26**: balancing using current transformers.*

□ I1: although in theory installing n links in parallel should enable the I1 of the assembly to be multiplied by n (each element only being traversed by I_N / n), in reality, this type of calculation is extremely dangerous as the slightest fault on one link will jeopardize the operation of the assembly.
Therefore, for safety reasons, the I1 of the component links of the assembly must be maintained.

□ I3: for fusing durations corresponding to I3, it is virtually impossible for all links to fuse simultaneously. Each link will fuse in turn.

This seems to suggest that the I3 of the assembly is that of the individual links. In this case, do not forget that the pre-arc durations are much longer than those of the individual links. The thermal conditions at the start of the arc are clearly different. Tests must be carried out in order to ensure that the break will continue to be effective.

■ In practice

In summary, the I3 of an assembly comprising n elements installed in parallel with an individual link I3 of $I3_0$, may have the value $I3_0$.
In the absence of tests or manufacturer specifications, assume a value of n $I3_0$.

□ Time/current characteristics: If a link blows in 1 second for a current I, n links will blow in 1 second for current n I. The time/current characteristic for the assembly will therefore be parallel to that for the basic links, offset by a multiplication factor on the current scale.

The tolerance in relation to I of the characteristic I(t) of a fuse is ± 10 %. In the case of parallel installation, any lack of symmetry is likely to reduce the duration of the pre-arc in relation to the theoretical curve.

In effect, none of the links are traversed exactly by I/n, but the one that is traversed by $I / n + \varepsilon$ will blow more quickly. This will then cause the other fuse links to blow very soon afterwards.

It is therefore advisable to apply a tolerance factor (+ 10 %, - 20 %) to the time/current characteristic of this type of assembly.

□ Limited cut-off current amplitude (see **fig. 27**).
The fact that Isc / n will flow through each link must be taken into account.
Therefore, if one link has a limit of Ipo, the assembly will have a limit of n Ipo.

■ Example

Take 2 links rated at 200 A, with a short-circuit current Isc of 50 kA
Ipo = I breaking if Isc = 25 kA or 22 kA peak (point **A**).

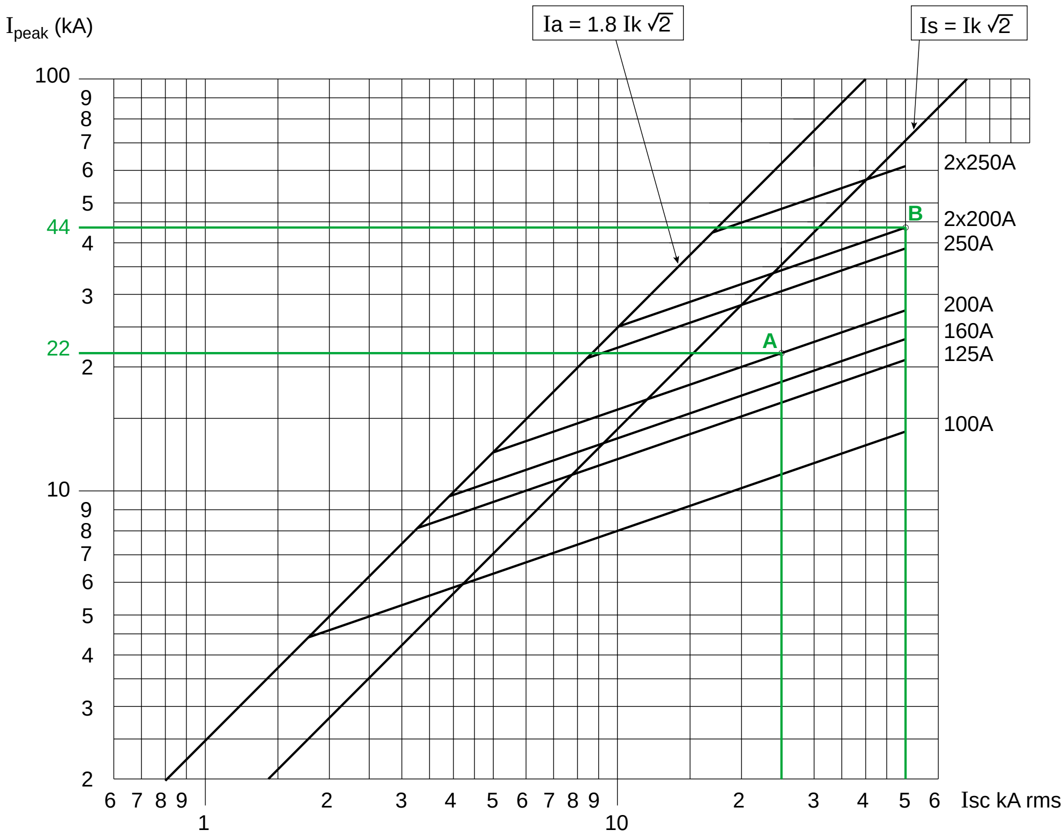


***Fig. 27**: current limitation curves according to rating (Fusarc-CF, Merlin Gerin brand).*

The assembly is therefore limited to
2 x 22 = 44 kA (point **B**).

■ Use

The usage regulations are the same as those for the individual fuse assemblies, based on the time/current characteristics.

Please also note:

□ do not forget to derate I_N by 20 %.

□ do not use the assembly excessively at its upper limits, particularly if the symmetry is not perfect (observe the tolerance limit - 20 % in relation to the time/current characteristics).

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