# COORDINATION OF FUSES AND OVERVOLTAGE PROTECTION DEVICES IN LOW-VOLTAGE MAINS

J. Schönau, F. Noack, R. Brocke
TU Ilmenau, Germany

## Summary

Fuses are used together with arresters in different types of overvoltage protection devices for low-voltage mains. The requirements on lv fuses which are installed in cascaded surge protection devices at the entrance of buildings are discussed. Experimental investigations on different sizes of lv fuses with lightning single pulse currents (10/350 µs) up to 80 kA deliver the behaviour of fuses in the prearcing phase. From this the permissible lightning pulse currents and the matching short-circuit currents were determined.

## 1 Introduction

Fuses are commonly designed, tested and used to interrupt short-circuit currents as well as long duration overcurrents. But it is a worldwide experience in distribution systems that fuses operate during thunderstorms and have to lead lightning currents.

In some countries it is a common method to use single-phase expulsion fuses for medium-voltage overhead line protection. Statistics from UK showed that most fuses blow during thunderstorms caused by no-damage transient phenomena [1]. Therefore these fuses were more and more replaced by other devices.

The nuisance operation of fuses on medium-voltage transformers during thunderstorms caused by long-duration lightning currents (amplitude less than 1 kA and some ms duration) was described in a Canadian paper [2]. This overcurrent operation is not a problem of the lightning current withstand of the fuses, but a problem of coordination of fuses, lightning arresters and transformers.

An other aspect of coordination between current limiting fuses and lightning arresters in medium voltage networks was described in [3]. When a current-limiting fuse interrupts a high fault current, the peak arc voltage over the fuse causes a discharge current through the arrester, which mustn't damage the protective device.

Also in the Australian medium-voltage networks the problem of nuisance fuse operations became important and the reasons were investigated in research projects. Laboratory tests with single puls lightning currents (8/20 µs to 40 kA, 4/10 µs to 80 kA) and multipulse currents (6 times 8/20 µs to 10 kA) were carried out on fuses up to 25 A current rating [4]. The results demonstrate that multiple lightning strokes with relatively small peak currents can vaporise fuses.

## 2 Fuses in low-voltage mains

Overvoltage protective devices in low-voltage mains are used in an ever increasing extent to protect the increasing number of sensitive electronic equipment like computers, information systems, control systems.

These problems of Electromagnetic Compatibility (EMC) become more and more important in low-voltage mains. In order to guarantee the undisturbed function of these vulnerable electronic systems the requirements on the overvoltage and overcurrent protection systems regarding protection levels and uninterruptible power systems (UPS) are much higher than for usual electrical installations. From this one has to see the fuses as a part of the protection systems which are installed mainly at the entrance of power lines into the buildings.

For the coordination of fuses and overvoltage protection devices in low-voltage mains only a few investigations are known. There is a long experience in European companies that surge arresters have included an internal disconnector for disconnection of the failed varistor from the main **(Fig. 1a)**. This combination of a special fuse and a disconnector avoids explosion or burning of the arrester during passage of large fault currents [5].

This arrester circuit guarantees an uninterrupted duty but the „protected loads" can be exposed by following transient overvoltages so long as the arrester has not been replaced.

An optional fusing circuit **(Fig. 1b)** was recommended by STANDLER [6] for use with suppressors on the low-voltage mains.

MOVS not protected?
when fail under
single. surge
condition.



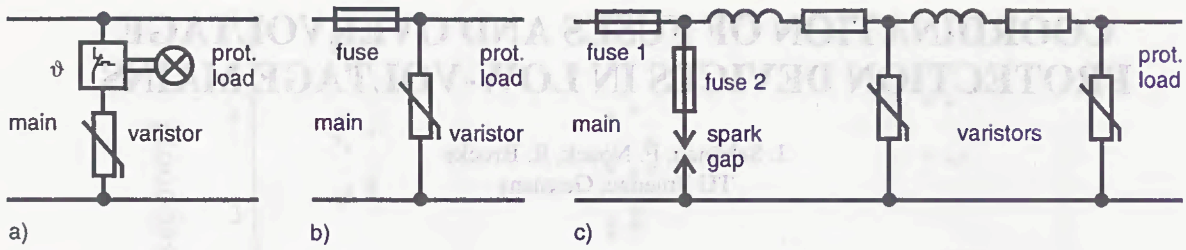


**Fig. 1a:** Low-voltage arrester equipped with thermal controlled disconnector and indicator circuit
**Fig. 1b:** „Open fail" fusing circuit for low voltage arresters
**Fig. 1c:** Cascaded surge protection device

The fuse will open not only during overload currents but also if the varistor fails. When the fuse opens, the protected loads are disconnected from the mains so that they will not be stressed to future overvoltages. However, the interruption of the power supply is often not acceptable. This technique is appropriate for use only in some special situations. The use of an adjusted fuse in series to the varistor will decrease the reliability of the surge protection, because the usual low-voltage fuses are more vulnerable to lightning surges than the varistors [7], [8].

Therefore the coordination of surge arresters and fuses in series in high reliable cascaded surge protection devices has to be considered even in the case of required high protection levels. In such a cascade (see **Fig. 1c**) some surge protective devices were installed in parallel, electrically separated by the impedance of the wiring inside the building.

The first surge protective device consists of a heavy duty spark gap which is able to lead lightning currents up to some 10 kA. From the manufacturers a fuse 2 series connected to the spark gap is foreseen, additional to the usual installed main fuse 1. During a lightning stroke the ligtning arresters operate and the lightning pulse current flows through the protective device and also through the fuses.

## 3 Requirements on the fuses

To guarantee the coordination between the elements during steady-state operation, short-circuit condition and lightning strikes too the fuses in **Fig. 1c** have to fulfill the following requirements:

- Fuse 1 is normally dimensioned to lead the load current and to protect the loads against overcurrents and short-circuit currents. The fuse must further lead the lightning current without melting, if an arrester operates during lightning strike, especially if the spark gap breaks through. In such a case after the lightning pulse a power frequency short-circuit current flows through the spark gap. Because the arc quenching capability of the spark gap is limited, the fuse has to protect the spark gap and to interrupt the short-circuit current if the limits will be exceeded. In some times it is difficult, to fulfill all these requirements in one fuse. Therefore it is necessary to install the additional fuse 2.

- Fuse 2 must also lead the lightning pulse current without melting and interrupt the short-circuit current through the spark gap. It is absolutely to avoid that this fuse, in series connected to the arrester and installed between phase conductor and earth, opens during the lightning puls. This severe requirement follows from the fact, that due to the high lightning overvoltage the melted fuse generates a relatively high arc voltage which can destroy the parallel arresters and also the sensitive loads. To guarantee the uninterrupted power supply the Joule-integral of fuse 2 should be less that this of fuse 1 (discrimination of the fuses). Consequently , the fuse 2 could be designed in an other way, because this fuse must not lead the continuous currents.

Depending on the peak value and the shape of the lightning current the fuses react in different ways:

- leading the pulse current without melting
- melting during the pulse
- exploding due to high energy

The behaviour of low-voltage fuses during lightning pulse stresses is widely unknown. Only some user-oriented tests were carried out on fuses with lower current ratings mostly using the 8/20 µs-pulse [7], [8].

Therefore investigation were performed on fuses, stressed by lightning pulses according to the new IEC-parameters.

# 4 Lightning current stresses of fuses

The parameters of the lightning threat are defined in IEC [9]. Because a ground flash is commonly composed of a number of separate different discharges (from one to more than 10 strokes) 3 types of stroke currents have been fixed: the first stroke, the long duration stroke and the subsequent stroke. Parameter for the different protection levels are shown in **Table 1.**

**Table 1:** Lightning current parameters acc. IEC (Secr.) 44

| | protection level I - IV | typical wave shape |
|---|---|---|
| first stroke<br>$T_1/T_2$ = 10/350 µs<br>peak current / kA<br>energy / MJ/Ω | <br><br>100 ... 200<br>2,5 ... 10 | ±i<br>t→ |
| long duration stroke<br>$T_d$ = 0,5 s<br>current / A<br>charge / As | <br><br>200 ... 400<br>100 ... 200 | ±i<br>t→ |
| subsequent stroke<br>$T_1/T_2$ = 0,25/100 µs<br>peak current / kA<br>mean steepness / kA / µs | <br><br>25 ... 50<br>100 ... 200 | -i<br>t→ |

If a building with external lightning protection system was hidden by a direct strike, the injected pulse current is distributed to the earthing system and to all conductive tubes and cables entering the building. Consequently, only a part of the lightning current will flow through surge protective devices.

The investigations were carried out with first stroke currents having a waveform 10/350 µs and peak values between 4 and 80 kA. Only these results will be discussed here. Also the effect of multiple pulses should not be considered.

# 5 Test arrangement

For the lightning current simulation a high-current coaxial pulse generator was used. The generation of high-voltage and high-current pulses is based on the discharge of a capacitor bank through a low-resistance discharge resistor. With variable resistors and inductances the same wave shape can be achieved at different pulse currents. The schematic view is shown in **Fig. 2.**

This design allows due to the high generator voltage up to 10 kV the injection of a load-independent current, that means the series connected spark gap with an arc voltage up to 200 V has no influence and can leave out for the test of the fuses.

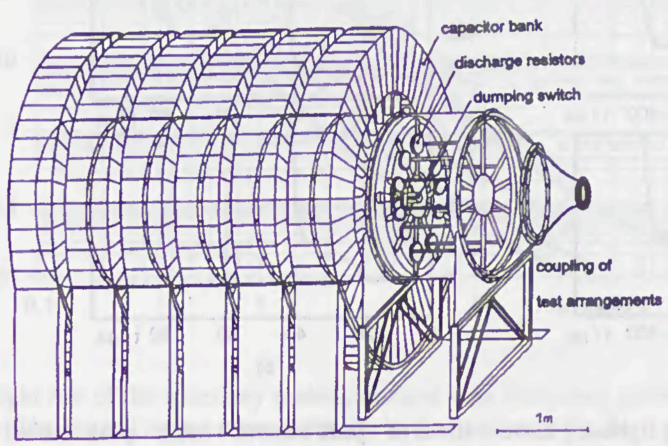


**Fig. 2:** Schematic view of the high-current pulse generator

A coaxial test arrangement including fuse, measuring shunt and voltage probe hase been designed, to make the magnetic field nearly symmetrically and to avoid magnetic forces during the arcing phase in the fuse (**Fig. 3**).

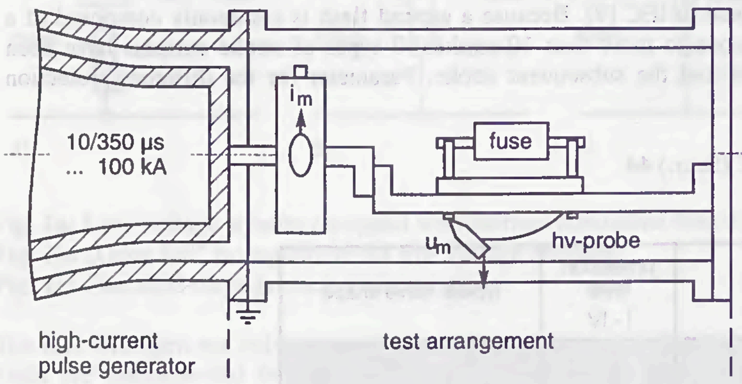


**Fig. 3:** Coaxial test arrangement

The sizes and rated currents of the tested „NH"-low-voltage fuses (rated voltage 500 V) are shown in **Fig. 4**.

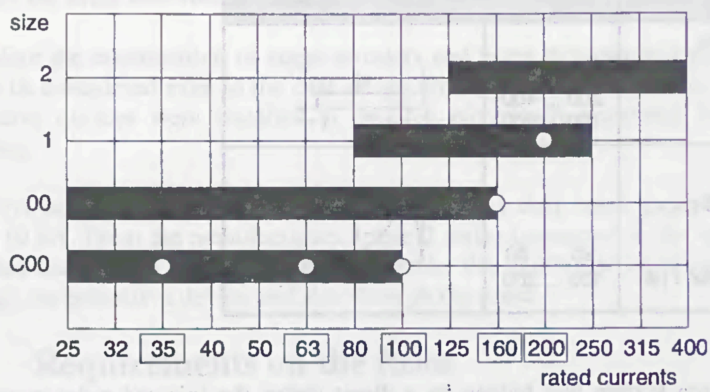


**Fig. 4:** Sizes and rated currents of the tested fuses

# 6 Experimental results

The fuses were tested by single pulses with increasing peak currents to obtain the stress limits during lightning strikes beyond there the fuses open. **Figure 5** shows the time behaviour of characteristic functions. Currents and voltages were measured, it is possible to calculate other values from the digital records.

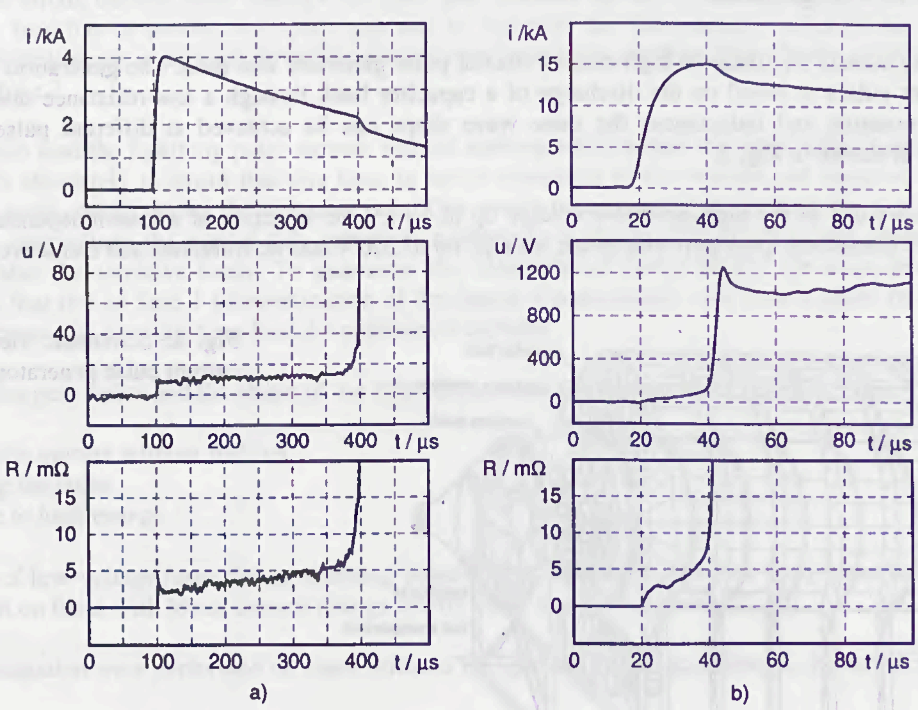


**Fig. 5:** Characteristic functions of fuses during lightning current stress (a - peak current 4 kA,b - peak current 15 kA)

If a fuse is stressed by a pulse with relatively small peak value the notches melt during the tail of the current pulse and the melting time is relatively long, e. g. some 100 µs. The higher the peak current the shorter the melting time down to some µs, that means the notches can melt during the rise of the pulse.

In order to compare the melting effect due to pulse currents with the usual power frequency fuse characteristics, the pulse melting currents were converted into rms-values (**Fig. 6**).

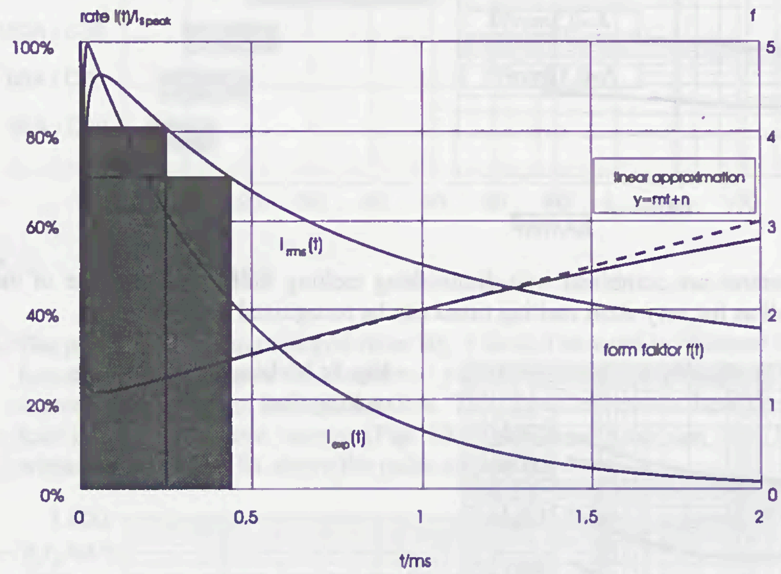


**Fig. 6:** Conversion of pulse currents into rms-values

The pulse melting integral values, calculated from these rms-values, and the melting times can be drawn in usual fuse characteristics (**Fig. 7**). The power frequency scatter bands of the different rated currents are defined by the standards. For every actual type of the investigated fuses also some 50-Hz-values were measured, which describe the transition to the pulse values.

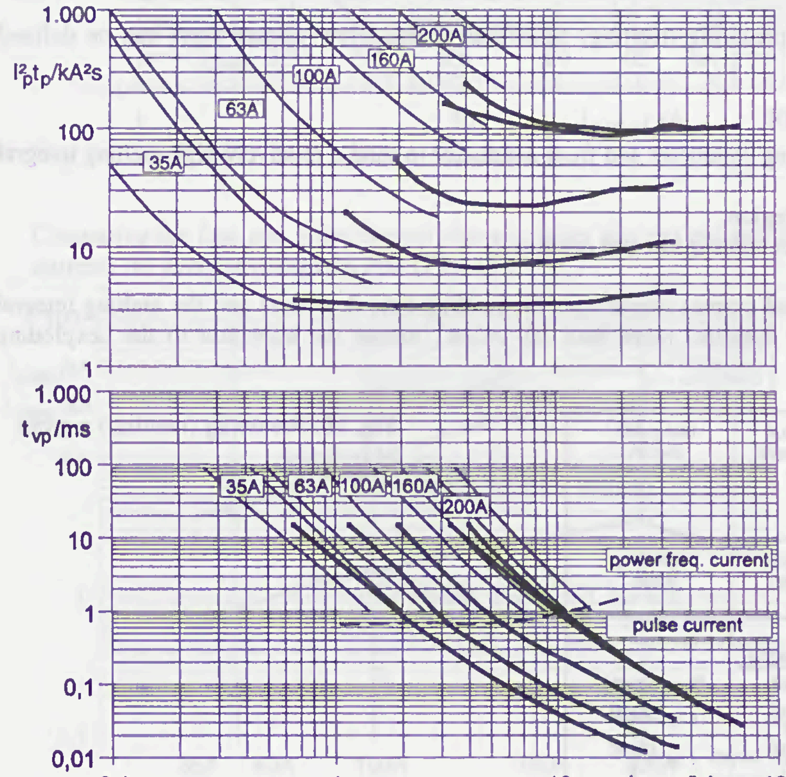


**Fig. 7:** Melting integral and melting time versus current rms-values ($I_p$ = prearcing current, $t_p$ = prearcing time, $t_{vp}$ = virtual prearcing time)

The slight rise of the necessary melting integral with increasing pulse current is also to obtain in the graph, showing the melting integral versus current density in the notches in **fig. 8**.

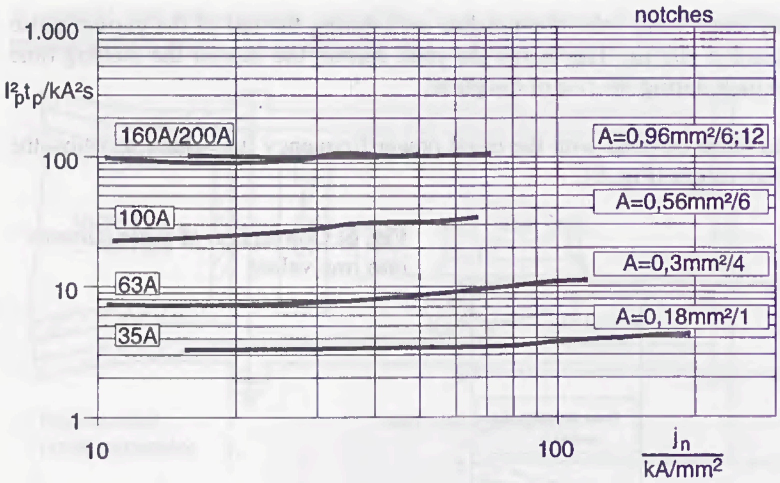


**Fig. 8:** Melting integral versus current density in notches

It is to consider, that increasing pulse currents are combined with diminishing melting times. The increase of the Joule integral for long melting times as well as for very short melting times can be recognized in **Fig. 9.**

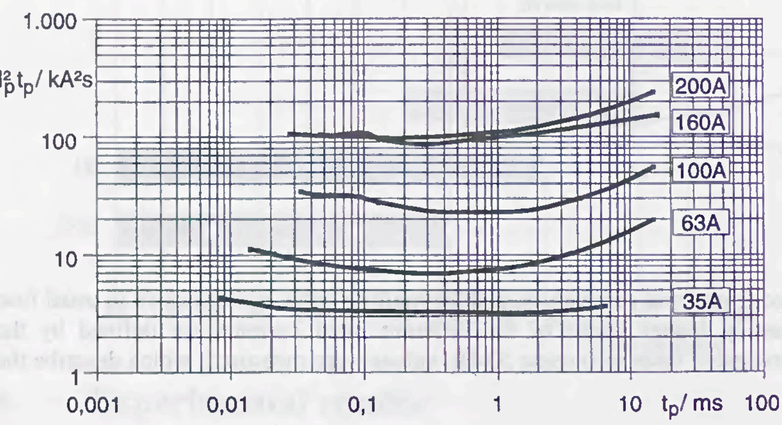


**Fig. 9:** Melting integral versus melting time

Regarding these results 3 regions in the prearcing (melting) behaviour of usual low-voltage fuses can be defined **(Fig. 10):**

a) Power frequency overcurrent region
Due to heat conduction inside the melting conductor and from conductor to sand a relatively high melting integral is necessary.

b) Short-circuit current and pulse current region
Under adiabatic conditions the minimum melting integral occures.

c) Fast pulse current region
With increasing pulse peak currents and current steepnesses the melting time decreases and the melting integral increases. This region, having current densities more than $10^7$ A/cm$^2$, means the transition to the „exploding wires“.

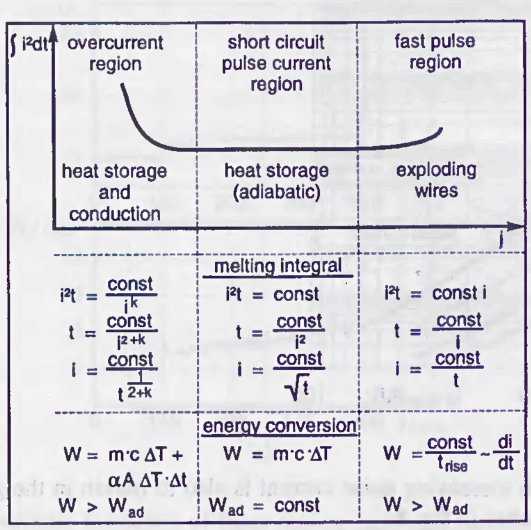


**Fig. 10:** Prearcing (melting) regions of lv-fuses

As explained before, the fuses can explode, if the pulse current exceeds specific limits. **Figure 11** illustrates these limits, depending on the lightning peak currents.

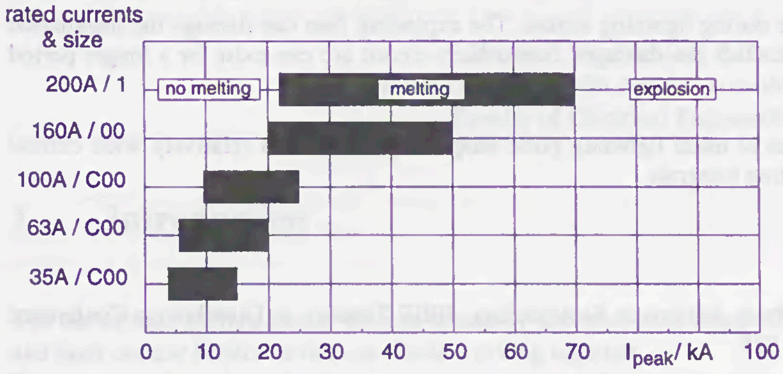


**Fig. 11:** Melting and exploding limits

# 7 Conclusions

1. The plot of the melting integral from **fig. 7** should be used to illustrate the pulse current withstand of low-voltage fuses. In this diagramm the connected points represent the change of the rms-values of a given lightning pulse current, depending on the melting time. This curve represents therefore the specific energy W/R of each injected load-independent pulse current **(Fig. 12)**. Only these fuses can lead 10/350 µs pulse currents without melting, whose scatter bands lie above the pulse current curve.

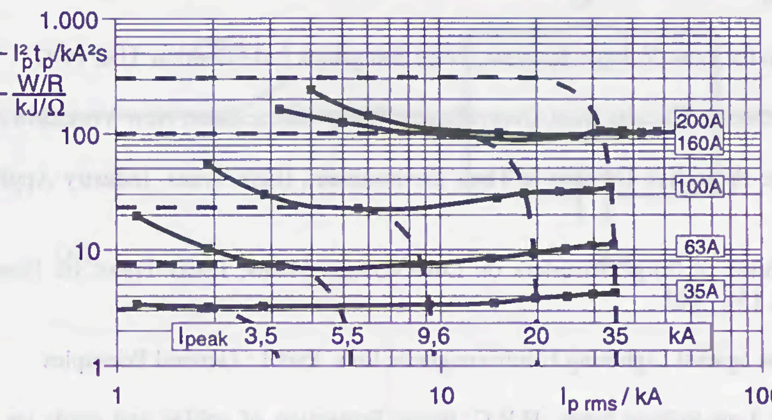


**Fig. 12:** Comparison of melting integrals and specific energies of lightning pulses

Comparing the fuse and pulse current characteristics one can indicate the permissible peak values of the lightning currents for every investigated fuse **(Fig. 13)**.

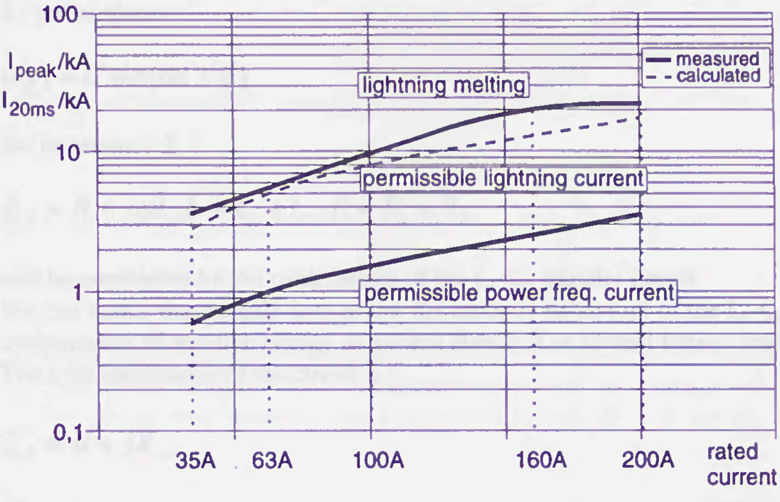


**Fig. 13:** Permissible lightning currents and 50-Hz-currents for lv-fuses

The lower limits of the permissible lightning currents were calculated by using the specific energy of the first stroke current and the minimum $I^2t$-values at $t_{vp}$ = 1ms for the different fuses, given by the standard [10].

From the coordination of arresters and fuses follows, that fuses must lead a power frequency current of given values without melting during a period of 20 ms. These permissible power frequency currents were also drawn in the diagramm. Therefore this diagramm shows the assignment of permissible pulse currents and short circuit currents to fuses with different rated currents.

2. It is to guarantee that fuses don't explode during lightning strikes. The exploding fuse can damage the installation and produce further short-circuit failures. Over the damaged fuse a short-circuit arc can exist for a longer period without current limiting effect.

3. The melting integral of low-voltage fuses at usual lightning pulse shapes represents in a relatively wide current range the attainable minimum of the melting integrals.

## References


[1] Rosen, P.; Golden, F.: A Single Phase Automatic Sectionaliser, IEEE Transm. a. Distribution Conference Anaheim, California 1986, p. 531- 538

[2] Hamel, A.; St.-Jean, G.; Paquetic, M.: Nuisance Fuse Operation on MV Transformers During Storms, IEEE Trans. on Power Delivery, Vol. 5(1990), No. 4, p. 1866 - 1874

[3] Muench, F. J.; Du Pont, J. P.: Coordination of MOV Lightning Arresters and Current Limiting Fuses, IEEE Trans. on Power Delivery, Vol. 5(1990), No. 2, p. 966 - 971

[4] Darveniza, M.; Mercer, D. R.: Field and Laboratory Studies of Nuisance Operation of Distribution Expulsion Fuses During Thunderstorms, Journal of Electrical a. Electron. Engineering, Australia, Vol. 12(1992) No. 4, p. 340 - 348

[5] Hasse, P.: Overvoltage Protection for Low-Voltage Systems, Peter Peregrinus Ltd., London, UK, 1992

[6] Standler, R. B.: Protection of Electronic Circuits from Overvoltages, Wiley-Interscience, New York, 1989

[7] Martzloff, F. D.: Matching Surge Protective Devices to Their Environment, IEEE Trans. Industry Applic. Vol. IA-21(1985), p. 99-106

[8] Birell, D.; Standler, R. B.: Failures of Surge Arresters on Low-Voltage Mains, IEEE Trans. on Power Delivery, Vol. 8(1993), No. 1, p. 156 - 161

[9] IEC 81(Sec.)57, 05/93: Protection against Lightning Electromagnetic Puls. Part 1.: General Principles

[10] DIN 57636/VDE 0636 Part 21: Low-voltage fuses, H.R.C. fuses: Protection of cables and cords up to 1 250 A and 500 V a.c., 440 V d. c. and 660 V a.c. (May 1984)