The influence of current frequencies up to 1.000 Hz on power dissipation and time-current characteristics of NH gG fuse-links

Michael Hausmann, Norbert Grass

GSO University of Applied Sciences Nuremberg, Kesslerplatz 12, 90489 Nuremberg,
michael.hausmann@ohm-hochschule.de, norbert.grass@ohm-hochschule.de

Abstract

In this paper, theoretical and experimental studies on the influence of higher frequencies of the load current on the power dissipation of NH gG fuse-links will be presented. By means of a power electronic converter, currents with variable frequencies and amplitude were fed thru NH gG fuse-links and model fuse-links with up to four parallel fusible conductors. The power dissipation and the pre-arcing times of the fuse-links have been compared at 50 Hz, 400 Hz and 1.000 Hz. Based on the power dissipation at different current frequencies, reduction factors for the fuse-link rated currents have been calculated, to obtain time-current characteristics similar to 50 Hz rated frequency currents. The pre-arcing times are shown in a time-current characteristic diagram of a standard fuse-link. The results are particularly gaining relevance due to increasing contents of harmonic currents in public grids and industrial plants.

Keywords: current frequencies, NH fuse-link, time-current characteristic.

1. Introduction

Today's power grids can have substantial amounts of harmonics or a higher base frequency in their voltage and currents. In airplanes for example, the board voltage has a base frequency of f = 400 Hz. In industrial grids, harmonics are generated by power electronic devices such as converters. These high frequency currents influence the behavior of the fuse-links. Standard fuse-links are designed for current frequencies of f = 50 Hz to 60 Hz. At these low frequencies the d.c. resistance dominates the behavior of the fuse-link.

At higher current frequencies the current thru the fuse is no more evenly distributed. This leads to higher power dissipation of the fuse-link and increasing temperature-rise. Due to this effect, premature operation of the fuse appears to be possible.

When feeding the fuse-link with high frequency currents the skin and proximity effect has to be considered. The skin effect describes the influence of the high frequency on the current density of one conductor. The proximity effect describes the influence of currents in different closely arranged conductors to each other. Both effects depend on the frequency of the current, the geometrical design of the fuse-link and the cable arrangement of the device where the fuse is installed [1-3]. All effects have an influence on the power dissipation and the pre-arcing time of the fuse-link. The effect of higher frequency currents is also described in [4] where also derating factors for the fuse links are calculated and discussed.

In this paper experimental results of measuring the power dissipation of a fuse-link are presented. During the experiments, fuse-links with parallel fusible conductors have been examined. As a result of the increased power dissipation, reduction factors for the rated fuse currents are calculated to obtain the same thermal behavior of the fuse compared to 50 Hz rated frequency. After that, the pre-arcing times of the fuses were drawn into a time-current chart of a standard fuse-link.

2. The experiment

In the experiment the fuse-links were loaded with currents of f = 50 Hz, 400 Hz and 1.000 Hz using a frequency converter. Due to the switching frequency of the converter, harmonic components in the fuse current are also generated. These harmonics can only be reduced by using large harmonic filters. So the harmonics of the fuse current were measured and then considered in the next calculations and simulations of the fuse-link.

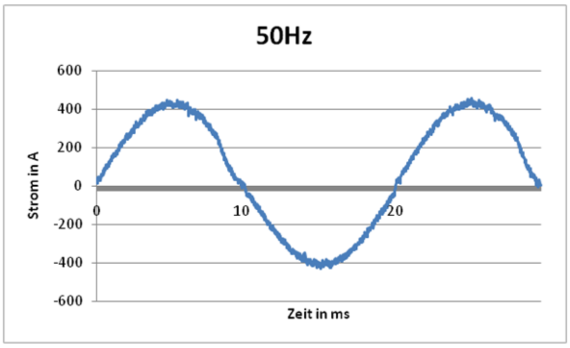

Fig 1: current with I = 300 A and f = 50 Hz

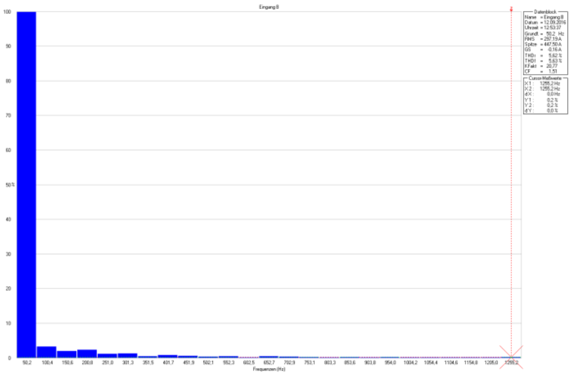

Fig 2: Harmonics at I = 300 A and f = 50 Hz

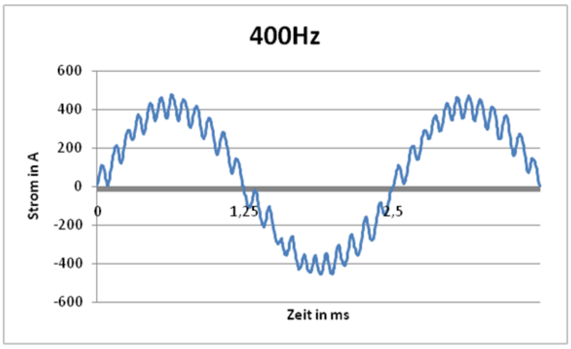

Fig 3: current with I = 300 A and f = 400 Hz

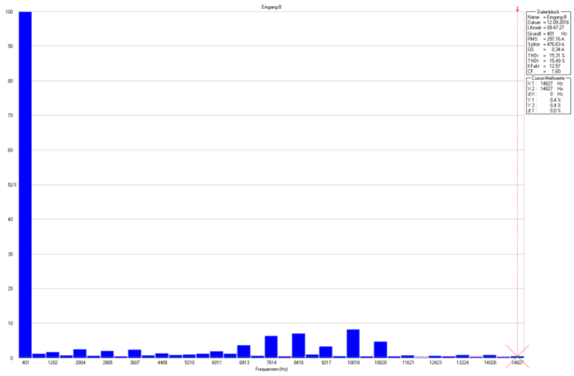

Fig 4: Harmonics at I = 300 A and f = 400 Hz

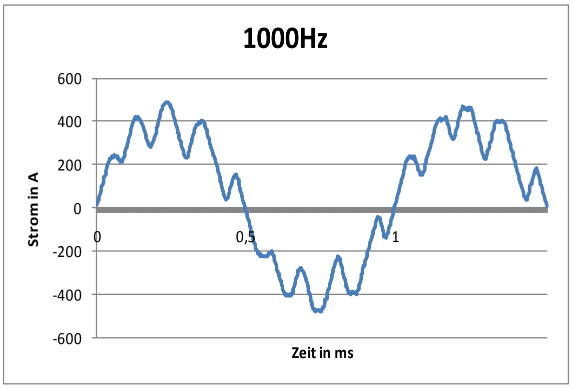

Fig 5: current with I = 300 A and f = 1.000 Hz

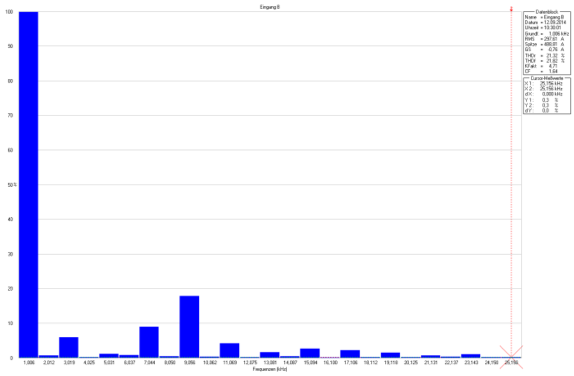

Fig 6: Harmonics at I = 300 A and f = 1.000 Hz

There is a significant difference in the fuse current harmonics between f = 50 Hz and f = 1.000 Hz. Due to the fixed switching frequency of the converter of f_s = 10 kHz, the contents of current harmonics are increasing with higher base frequencies (see Fig 1 to Fig 5 6?). Nearly no switching frequency can be seen when generating currents of f = 50 Hz.

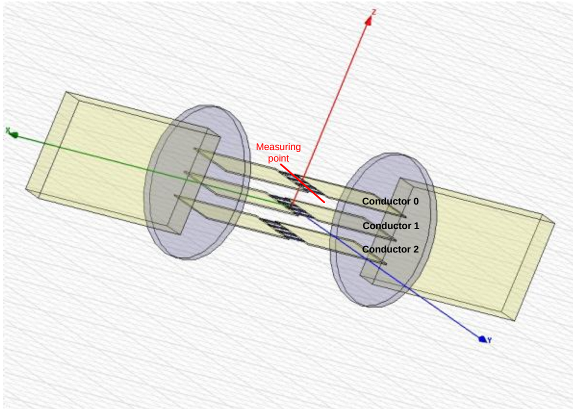

Fig 7: model of the fuse-link in Maxwell 3D simulation program

Fig 7 shows the 3D model of a fuse-link with three parallel fusible conductors. It is assumed that one fusible conductor can carry a current of I = 100 A. All the effects on the fuse-links were referenced with a 3D finite element simulation using Maxwell 3D simulation tool.

2.1. The Skin Effect

Equation (1) shows the calculation of the skin effect in a round conductor [5].

$$\delta = \sqrt{\frac{2}{\omega \cdot \mu \cdot \kappa}} \qquad (1)$$

With:

$$\omega = 2 \cdot \pi \cdot f$$

μ = Permeability,

κ = electric conductivity

With equation (1) the eddy current depth at f = 1.000 Hz is 2,1 mm. Due to this equation, the skin effect has no influence on the 0,5 mm thick conductor.

The skin effect can be seen on the finite element simulation results (see Fig 8). In the simulation a flat rectangular conductor was fed with currents of f = 100 Hz, 1.000 Hz and 10.000 Hz. The simulation results in Fig 8 show that the current density is higher at both edges of the conductor than in its center.

The skin effect must be calculated using equation (2) [5]. In this equation the current density can be calculated over the width of the conductor.

$$J_x(z) = \frac{I_0}{2 \cdot b} \cdot \gamma \cdot \frac{\cosh(\gamma \cdot z)}{\sinh\left(\gamma \cdot \frac{d}{2}\right)} \qquad (2)$$

The calculated current density was checked with the finite element simulation. The simulation results were normalized to get a current independent distribution of the densities.

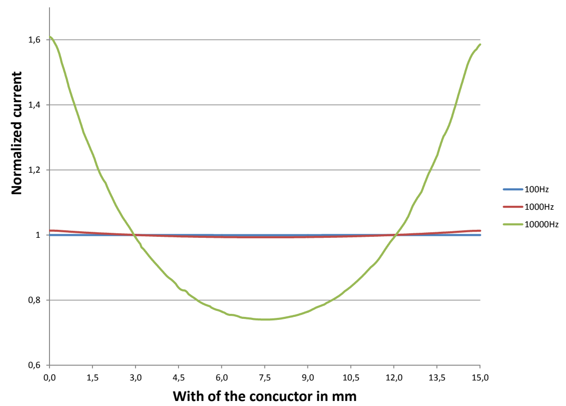

Fig 8: Current density in a flat rectangular conductor over the widths of the conductor

The simulation results in Fig 8 show the power density over the width of the conductor.

The effect is stronger at current frequencies of f = 10.000 Hz but can also be identified at frequencies of f = 1.000 Hz. At lower frequencies, the current density of the fusible conductor is approximately homogeneous.

2.2. The Proximity Effect

The proximity effect describes the influence of currents in different adjacent conductors. The effect depends on the geometric arrangement of the fusible conductors [2, 6]. In the experiment, only parallel conductors were considered (see Fig 7). In order to obtain a realistic model of the fuse-link, the 3D model was built after a real fuse-link. Restrictions were placed in the center of the fusible conductors to achieve a current density similar to that of a real fuse.

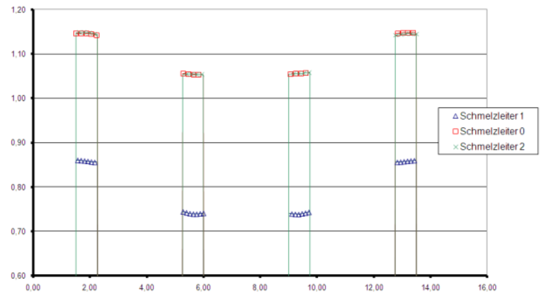

Fig 9: Current density in a fuse-link with three fusible conductors an a current with f = 1.000 Hz

The simulation results in Fig 9 show the skin- and proximity effects. The current density is increased in the edges if only one fuse-element is considered. This comes from the skin effect in the single conductor.

The current densities in both outer conductors (conductors 1 & 2) are higher than the density in the center conductor. This effect can be seen in every fuse-link with a minimum of 3 conductors.

Due to the two effects, there is a change of the a.c. resistance $R_\sim$ of the fusible conductors shown in equation (3) [5].

$$R_\sim = R_- \cdot Y_{Skin} \cdot Y_{Prox} \qquad (3)$$

In this equation, the d.c. resistance of the fuse-link is influenced by two factors. One factor for the skin and one for the proximity effect ($Y_{Skin} \cdot Y_{Prox}$). The values for these correction factors are greater than 1. That means, with higher current frequency the resistance of the conductor increases. Because of the higher resistance, the power dissipation and the temperature rise of the fuse-link will increase.

3. Heating behavior of the fuse-link

Due to the assembly of the fuse-link, the power dissipation of the fuse-link is generally low. In fuse-links with 3 or 4 conductors, the one or two conductors in the center of the fuse-link are having higher temperatures than the two outer ones (see Fig 10).

To obtain more information on the temperature distribution inside the fuse-links, a temperature measurement was taken. For this experiment a fuse-link body was opened and filled by half with sand, leaving the edges if the fusible conductors exposed. After that, the open fuse was subjected to currents of I = 100 A with f = 50 Hz and f = 1.000 Hz.

Fig 10 shows the temperature distribution of a fuse-link with three conductors. The fusible conductor in the center of the fuse heats up to 70°C. The two outer conductors to 60°C. This effect takes place independent on the current frequency.

Due to this effect the solder of the center conductor would melt first and initiate fuse operation.

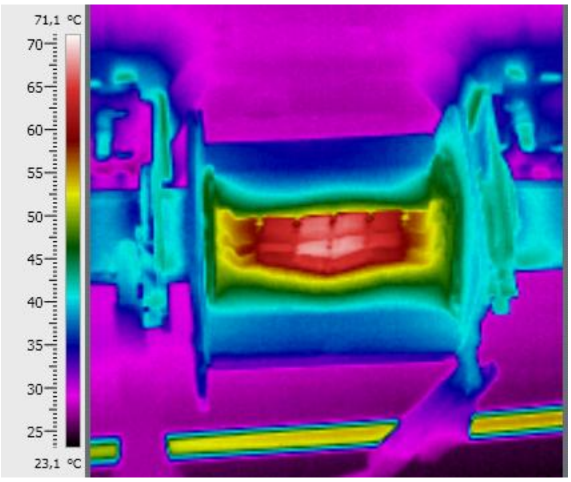

Fig 10: Temperature rise of a fuse-link model with three parallel conductors

4. Power dissipation of the fuse-link

In the experiment, fuse-links with one to four fusible conductors have been investigated. The experiment was split in two steps. In the first step the fuses were fed with their “rated” currents. It was assumed that each conductor can carry a current of I = 100 A. The current frequencies were changed in three steps from f = 50 Hz to 400 Hz and 1.000 Hz.

In the second step the currents were increased to 1,6 times and 2,5 times their “rated” currents.

During the tests, the current, the voltage and the temperature of the fuse-links were recorded every 60 s. The different experimental steps can be seen in Table 1.

Fig 11 shows the power dissipation of a 400 A fuse-link with four fusible conductors at the three different frequencies.

Table 1: Table of the measurements

	Frequency	Fuse type			
Nominal fuse current		100A	200A	300A	400A
Number of fusible conductors		I	II	III	IIII
Heating treatment with hominal fuse current	50Hz	1	1	1	1
	400Hz	1	1	1	1
	1000Hz	1	1	1	1
pre-arching times with 1,6 times the nominal current	50Hz	1	1	1	1
	400Hz	1	1	1	1
	1000Hz	1	1	1	1
pre-arching times with 2,5 times the nominal current	50Hz	1	1		
	400Hz	1	1		
	1000Hz	1	1		

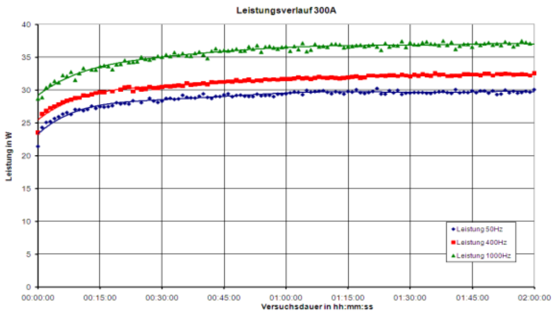

Fig 11: Power dissipation of a fuse-link with 4 fusible conductors at different frequencies

It can be seen that the power dissipation rises with increasing current frequencies. The temperature and power dissipation of the fuse-link changes the same way. After starting the experiment the power dissipation rises and finally reaches a steady state.

Fig 12 shows the steady state values of power dissipation of the fuse-links over the different frequencies. The figure shows a linear rise of power dissipation with increasing current frequencies.

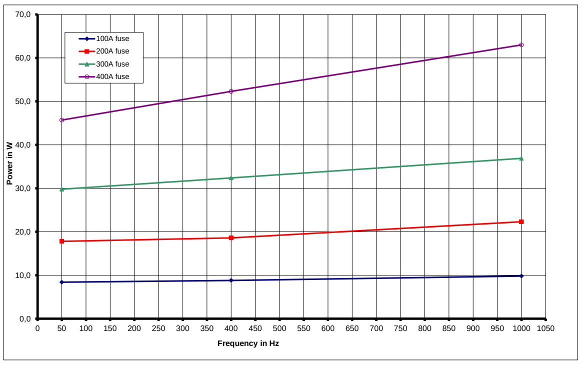

Fig 12: Power dissipation of the fuse-links over the frequency at “rated” currents of the fuse-links

Due to the linear dependence of the power dissipation of the fuse-links and the current frequency, a correction factor for the fuse rated current can be calculated. With this factor the maximum current of a fuse-link can be calculated that results in a similar thermal behavior than a 50 Hz current.

5. Calculation of the correction factors

$$P = I^2 \cdot R \tag{4}$$

Equation (4) shows the power dissipation of the fuse-link in dependence of its resistance R and the current I thru it. The resistance R represents the a.c. resistance in dependence of the skin and proximity effects. The a.c. resistance is independent on the fuse current. To obtain equal power dissipation at high frequency currents, the current thru the fuse-link has to be reduced.

In the next equations, a correction factor for a 400 A fuse-link at f = 1.000 Hz is calculated.

$$P_{50Hz} = I^2 \cdot R_{50Hz} = P_V = I_v^2 \cdot R_{1000Hz} \tag{5}$$

To get the reduced current I_V of the fuse, the power dissipation in the conductors at f = 50 Hz must be the same as the power dissipation with reduced current at f = 1.000 Hz (see equation (5)). After solving equation (5) to the currents, a ratio in dependency of the resistances can be calculated using equation (6).

But there is no information about the a.c. resistances of the fuse-link at any frequency. So equation (6) has to be modified to obtain a suitable correction factor.

$$I_{50Hz}^2 \cdot R_{50Hz} = I_v^2 \cdot R_{1000Hz}$$
$$\rightarrow \frac{I_{50Hz}}{I_v} = \sqrt{\frac{R_{1000Hz}}{R_{50Hz}}} \tag{6}$$

The reduced current through the fuse can be calculated using the measured power dissipation. To obtain an equation for the ratio of the currents in dependency of the power dissipation, the frequency specific equations (5) has to be inserted in equation (6).

$$\frac{I_{50Hz}}{I_v} = \sqrt{\frac{P_{1000Hz}}{P_{50Hz}}} = \frac{1}{k} \tag{7}$$

Equation (7) shows, that the f = 1.000 Hz current has to be reduced, in order to obtain a similar behavior than with the f = 50 Hz current. In equation (8) the correction factor is calculated for a 400 A fuse at a current frequency of f = 1.000 Hz.

The equation shows, using the measured power dissipation of the fuses, the current has to be reduced to $I_V = 341A$.

$$\frac{I_{50Hz}}{I_v} = \sqrt{\frac{P_{1000Hz}}{P_{50Hz}}} = \sqrt{\frac{63W}{45,7W}} = 1,174 = \frac{1}{k}$$
$$k = 0,852 \tag{8}$$
$$I_v = I_{50Hz} \cdot k = 400A \cdot 0,852 = 341A$$

Using the power dissipation of the experiment, the factors for the skin and the proximity effects for higher frequencies can be calculated.

$$R_{1000Hz} = R_{50Hz} \cdot Y_{Skin} \cdot Y_{Prox} = \frac{R_{50Hz}}{k^2} \tag{9}$$

As shown in equation (9), the calculated correction factor k stands for the two factors Y_{Skin} and Y_{Prox} of the fuse with 4 fusible conductors. An emphasis of the skin or the proximity effect can't be seen. The factor for the skin effect can be calculated from the measurement results with one fusible conductor. In this measurement, only the skin effect takes place. It is nearly the same factor for fuse-links with more conductors. Typically, the proximity effect has an increased influence of the power dissipation in the conductors.

$$Y_{Skin} \cdot Y_{Prox} = \frac{1}{k^2} \tag{10}$$

The second step of the experiment shows that the calculated reduction factors for the currents for $I = 1,6 \cdot I_N$ and $I = 2,5 \cdot I_N$ times the nominal current are similar.

As a next step the pre-arcing times of the fuse-links at higher frequency currents were plotted in a time-current characteristic diagram of a standard fuse-link. It has to be considered that the examined model fuse-links had identical parallel fusible conductors taken from a standard 100 A gG fuse-link and therefore had an inferior thermal behavior compared to standard fuse-links. To fit the measured pre-arcing times into a time-current chart of a standard fuse-link the “rated” currents of the fuses had to be adjusted to more realistic values.

The adjustment was based on the power dissipation of the fuse-links. If a standard fuse-link with one single fusible conductor has a power dissipation of $P = 8,4W$ a fuse-link with two fusible conductors should have a power dissipation of $P = 16,8W$. The corresponding model fuse-link tested exhibited a power dissipation of $P = 20W$, which represents a 19% increase Considering equation (4), a standard fuse-link can carry a current increased by 9% of its rated current to dissipate the same power.

To plot the measured results in a time-current diagram of a standard fuse-link the “rated” currents of the tested sample fuses had to be corrected by a factor as shown in Table 2. After adjusting and normalizing the rated currents of the tested fuse-links, the pre-arcing times of the fuses can be plotted in a time-current chart of a standard fuse-link as shown in Fig 13.

Table 2: Adjustment factors for rated currents of the model fuse-links to compare with standard fuse-links

Umrechnung der Stromwerte

		I	II	III	IIII	
P_N	50 Hz	8,4	20,00	33,00	48,00	W
P_N	Faktor	1	1,19	1,31	1,43	W
I_N	Faktor	1	1,09	1,14	1,20	A
P_N	400 Hz	9,5	25,50	38,50	55,00	W
P_N	Faktor	1	1,34	1,35	1,45	W
I_N	Faktor	1	1,16	1,16	1,20	A
P_N	1000 Hz	9,25	25,00	50,00	85,00	W
P_N	Faktor	1	1,35	1,80	2,30	W
I_N	Faktor	1	1,16	1,34	1,52	A

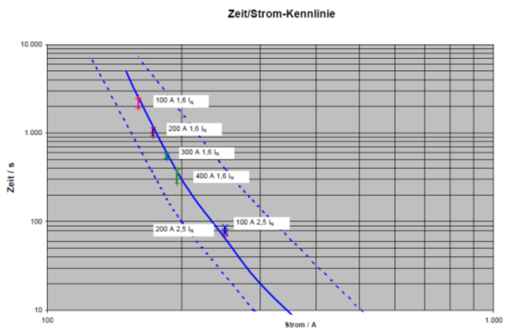

Fig 13: Pre-arcing times of the model fuse-links adjusted to time-current characteristics of standard gG fuse-links

6. Conclusions

By feeding higher frequency currents thru standard NH gG fuse-links, higher power dissipation of the fuses is generated. Due to the higher power dissipation, the temperature-rise of the fuse increases over rated values. After a sufficient temperature-rise, fuse operation will be initiated at rated current or even below.

The two main effects for this rise in power dissipation and temperature are the skin and the proximity effects. They were investigated by calculation and 3D finite element simulation using Maxwell simulation tools.

In an experiment, different fuses with different numbers of parallel fusible conductors were loaded with higher frequency currents. The voltage and currents on the fuses were measured to obtain the power dissipation of the fuse-links. With these power dissipation values, reduction factors for the fuse rated currents are calculated for similar power dissipation of the fuse as at rated frequency currents.

After normalizing the rated currents of the tested model fuse-links with parallel conductors the pre-arcing times of the fuses could be drawn in a standard time-current characteristic and compared to standard characteristics.

Now, the same experiment could be done with standard fuse-links to examine the influence of the proximity effect on the standard fuses. Then modified rated currents and pre-arcing times could be defined too.

It has expired that the thermal effect of higher frequency currents have to be considered and reduction factors applied when calculating the maximum load of fuses and fuse gear. The effects on time-current characteristics, however, appear to be within the limits of normal fuse tolerances.

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USE OF LOW-VOLTAGE FUSE-LINKS IN SWITCH UNITS LIKE FUSE – IMPACT ON POWER DISSIPATION AND POSSIBLE MISHAPS AT OVERLOAD AND SHORT-CIRCUIT CURRENT BREAKING

Branko Pesan