The influence of important ageing mechanisms on long-term behavior and reliability of fuse-links at higher temperatures

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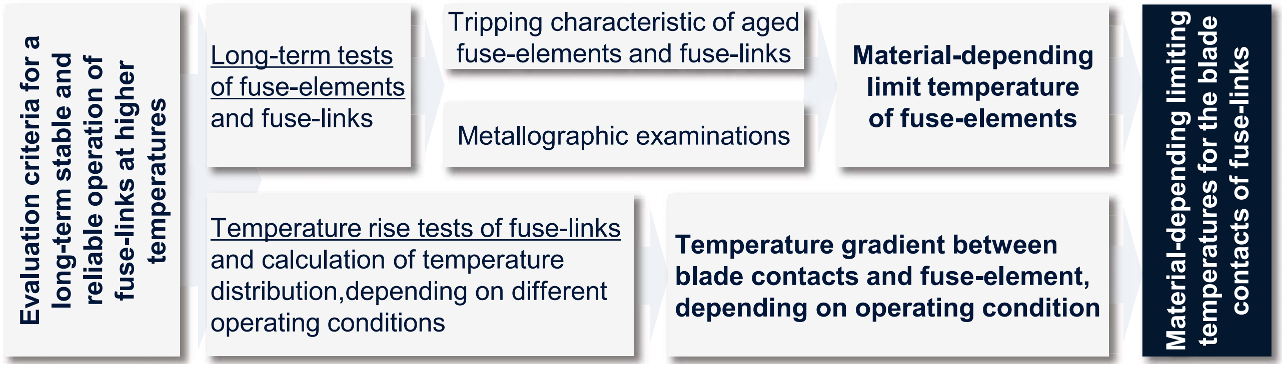
Introduction

In the last decades a comparatively simple and cost-effective design combined with a high reliability led to a great success of low-voltage high-rupturing-capacity fuses (NH-system) in the field of overcurrent protection devices. For reaching a high security of supply a faultless function of these fuses is essential at all operating conditions. Economic aspects and increasing current load lead to higher requirements on fuses. Thus, the fuse-link's load profile changes increasingly too. These economic aspects and a growing need for safety lead to more compact and encapsulated substations too. Due to a growing secondary feed-in at low-voltage grids, original distribution substations are changing to feed-in substations with a constantly high current load. Furthermore, the trend of continuously growing limiting temperatures brings about distinct higher thermal stress of fuses. Since the fuse tripping characteristic is directly influenced by these environmental conditions, higher thermal stress can result in accelerated ageing of the fuse-elements and can lead to unintended tripping or even cause the tripping to fail.

To avoid these failures by accelerated ageing of the fuse-elements, criteria for a long-term stable and reliable operation should be specified. Limiting temperatures of the blade contacts might be a suitable criteria as the blade contacts are thermally well linked with the fuse-element and temperature measurement is not that complicated. Therefore the temperature gradient between the blade contacts and the fuse-element must be known as well as the fuse-element's maximum temperature, depending on the material, to avoid accelerated ageing (Picture 1).



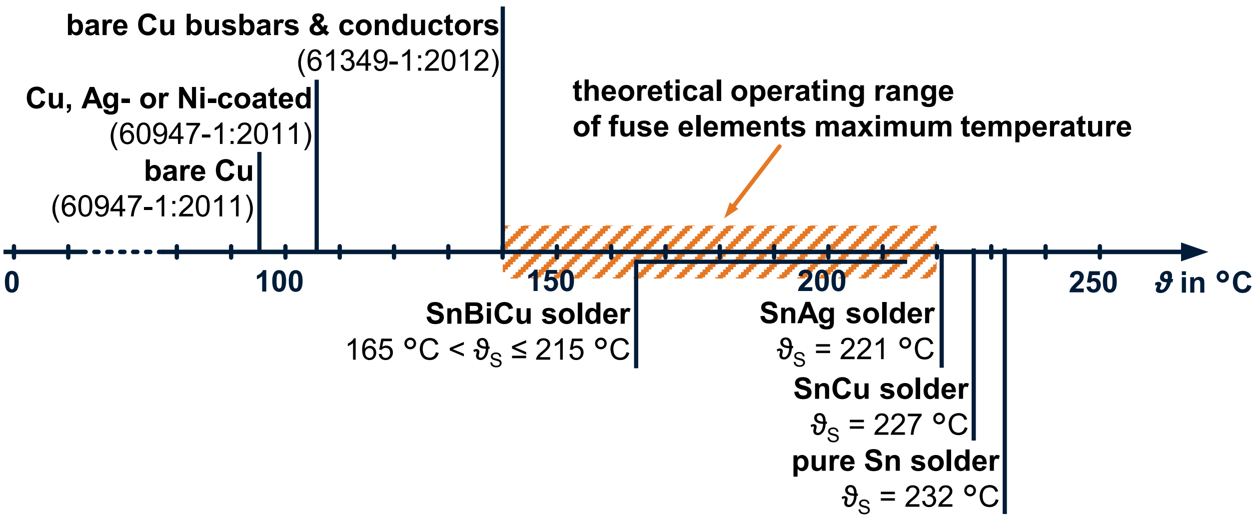
Picture 1: Planned investigations to specify material-depending limiting temperatures of fuse-links (initial investigations of underlined parts are presented subsequently)

As a first step the influence of major ageing mechanisms on the long-term behavior of fuse-elements and the thermal behavior of the corresponding fuse-links were investigated.

Current operating conditions and thermal requirements

As already mentioned, the maximum fuse-element's temperature is the most suitable value to detect and evaluate the fuse-link's current operating point. Its possible operating range is limited by several requirements and conditions, respectively. The balancing act of low power losses and fast tripping has to be mastered as well as a certain robustness should be provided to guarantee a relatively long service life.

Thereby, the upper end of operating range is limited by the physical property of solder's melting temperature obviously. Depending on the additional alloying elements of tin based solders the melting temperature can vary much from 165 °C for SnBiCu solder up to 227 °C for a SnCu solder (Picture 2) [1], [2]. The bottom end of the operating range is limited by ambient conditions and the temperature gradient between the blade contacts and the fuse-elements maximum temperature. Thereby, ambient conditions mean the ambient temperature, which can rise up to 50 °C in installation position [3] as well as the temperature of adjacent components, e. g. busbars or cable outlets. Their limiting temperatures reach from 95 °C for bare copper contacts up to 140 °C for copper busbars or conductors and special boundary conditions, according to [4] and [5]. Hence a theoretical operating temperature range results between 140 °C and 227 °C, in which the fuse-element might be able to operate. It is not clear how much the fuse-element's permanent temperature can be raised without compromising a reliable and long-term stable operation. One major goal of the current investigations is to determine these unknown limiting temperatures depending on the solder alloy.



Picture 2: Theoretical operating range of fuse-elements maximum temperature between limiting temperatures of adjacent components and solder's melting temperatures

Ageing of full-range general purpose fuse-links (gG)

Higher thermal stress, caused by increased ambient or operating temperatures, can result in an accelerated ageing of the fuses. Thereby, ageing in general is defined as an unintended deterioration of fuse's properties, which impairs its functionality [6]. In the solder plated fuse-element's area the interdiffusion between the solder and the fuse-element's base material as well as chemical reactions, e.g. oxidation of the solder depot itself, can be considered as the major ageing mechanisms.

1_Interdiffusion

The mechanism of disconnecting overloads is based on the physical mechanism of interdiffusion between fuse-element's base material and the solder. Once the solder is molten, this reaction takes place very fast and initiates the fuse-link's tripping. Obviously the interdiffusion also occurs already below the solder's melting temperature with a slower temperature-dependent reaction speed.

In the field of full-range NH-fuses for general purpose (gG) copper with a tin based solder is the almost exclusively used material combination for the fuse-elements. At the Cu-Sn system three IMCs, Cu_3Sn and the tin-rich phases Cu_6Sn_5 and Cu_6Sn_5' can be formed [1]. Due to higher thermal stress, the increased growth of IMCs at the interface could have different consequences. Obviously higher operating temperatures lead to accelerated interfacial reactions. Therefore, fusing starts already at lower currents than the original 160 % of rated current and might cause unintended shutdowns in consequence [8]. On the other side, it might be possible that the fuse-element would be overstressed for relatively short intervals only, which are not long enough for fusing. Alternatively, the applied thermal load is not that high but therefor it occurs for a relatively long period. Thus, at the interface thin IMC layers can be formed. They are not thick enough to reduce the fuse-element's cross section and increase the electrical resistance in that area significantly. But it might be possible that this layers could act as a barrier for the interdiffusion in case of overloads, because of a decreasing concentration gradient. Thus, fusing won't be achieved because of too slow reaction and the fuse-link won't be able to operate but gets continuously hotter and could explode in worst case.

2_Chemical reactions

In the field of full-range fuse-links the oxidation of the solder is of particular interest as the solder is essential for a successful interruption of overloads. The used solder is commonly a tin based solder, with a relatively high percentage of tin. Under normal atmospheric conditions pure tin forms impurity layers like oxides on its surface, which don't have a protective effect on the remaining tin volume like other metal oxides have. Thus, the remaining solder volume decreases continuously. A successful fuse operation in case of overload might be threatened, because there is a minimum amount of solder needed so that the interdiffusion takes places sufficiently fast. Since the oxidation is a temperature-dependent reaction too, it's getting more and more relevant with increasing thermal stress of fuse-links at normal operating conditions.

Long-term tests of fuse-elements

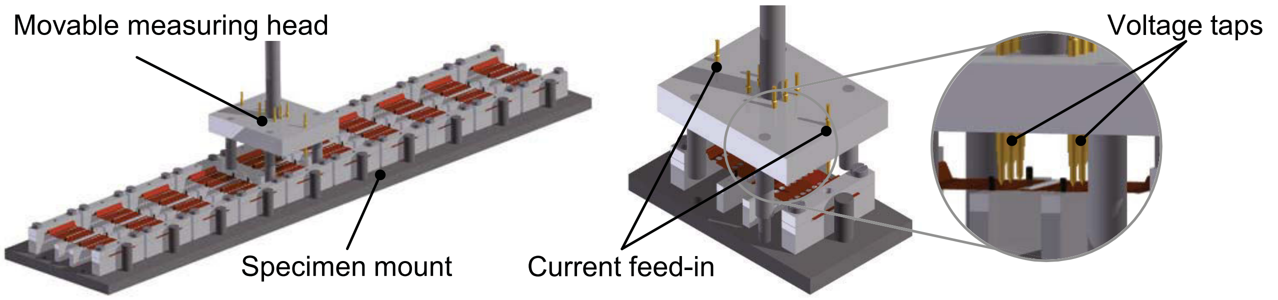
1_Experimental setup

For investigating the consequences of increasing interdiffusion and oxidation at the fuse-element's properties, long-term tests at different temperatures are conducted in which the fuse-elements are heat-treated in ovens. Three different fuse-elements are investigated. All fuse-elements are used in current general purpose fuse-links with the same parameters. According to the identified theoretical operating range (Picture 2) fuse-elements are heat-treated at different temperatures between 140 °C and 220 °C (Table 1).

Table 1: Design of experiments – fuse-elements and properties of based NH-fuse-links [1]

Fuse-elements				Specimens per temperature step						Parameters of based fuse-links
Type			ϑ_M in °C	140 °C	160 °C	180 °C	200 °C	210 °C	220 °C	
A	Cu	SnBiCu	165 - 215	10	10	-	-	-	-	•gG •U_r = 500 V •NH 2 •I_r = 250 A
B		SnAg	221	-	10	10	10	10	-	
C		SnCu	227	-	10	10	10	10	10	

In order to assess the changes caused by ageing, the electrical resistance of each fuse-element is measured periodically at ambient temperature. A high sensitivity is reached by measuring directly the resistance of the solder deposited area with a common four probe test setup. Therefore a special specimen mount was designed which fixes the fuse-element for repeatable resistance measurements and avoids mechanical stresses caused by different linear expansion coefficients too (Picture 3).



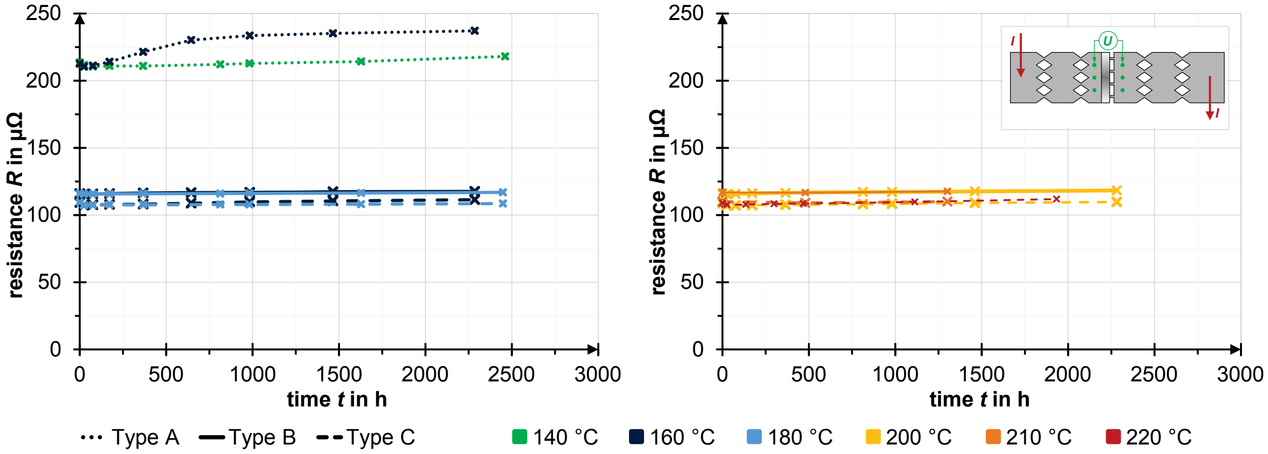
Picture 3: Specimen mount and movable measuring head for resistance measurement

The base plate is made of steel with a similar linear elongation like the fuse-elements. Clamping connections made of PTFE fix the specimen on the base plate and isolate the specimens electrically from it. Furthermore, longitudinal and transversal stops are used for accurate positioning and reproducible resistance measurements. With a moveable measuring head the current is applied at the end of the fuse-element and the resulting voltage drop is measured at three single positions at the solder deposited area and averaged afterwards (Picture 3). For a constant contact pressure and reliable measurements in case of relatively thick oxide layers too, gold coated spring contacts with a sharp tip and a spring force of 3 N at working travel have been used, both for current feed-in and voltage taps.

The measuring head is only used at ambient temperatures and can be removed for heat treatment. For measuring the electric resistance a microohmmeter (LoRe by Werner Industrielle Elektronik) is used. To avoid unintended heating of fuse-elements during the measurement, a maximum current of I = (1…2) A is applied.

2_Results and discussion

To analyze the ageing behavior depending on duration and temperature of heat treatment, the average value and standard deviation of the measured resistances have been determined (Picture 4). The different fuse-element types vary in geometry and quantity as mounted in the corresponding fuse-links. In consequence, the initial readings vary considerably too and are not directly comparable.



Picture 4: Electrical resistance of solder deposited area, depending on duration and temperature of heat-treating (standard deviation is not plotted in favor of a better overview; $\sigma \leq 1$ µΩ applies in general)

For the fuse-elements with SnCu and SnAg solders (type B and C) up to a temperature of 210 °C no significant changes of the electrical resistance could be measured after heat treatment of 2000 h. Furthermore, no significant impurity layers like oxides could be identified on the solder's surface yet.

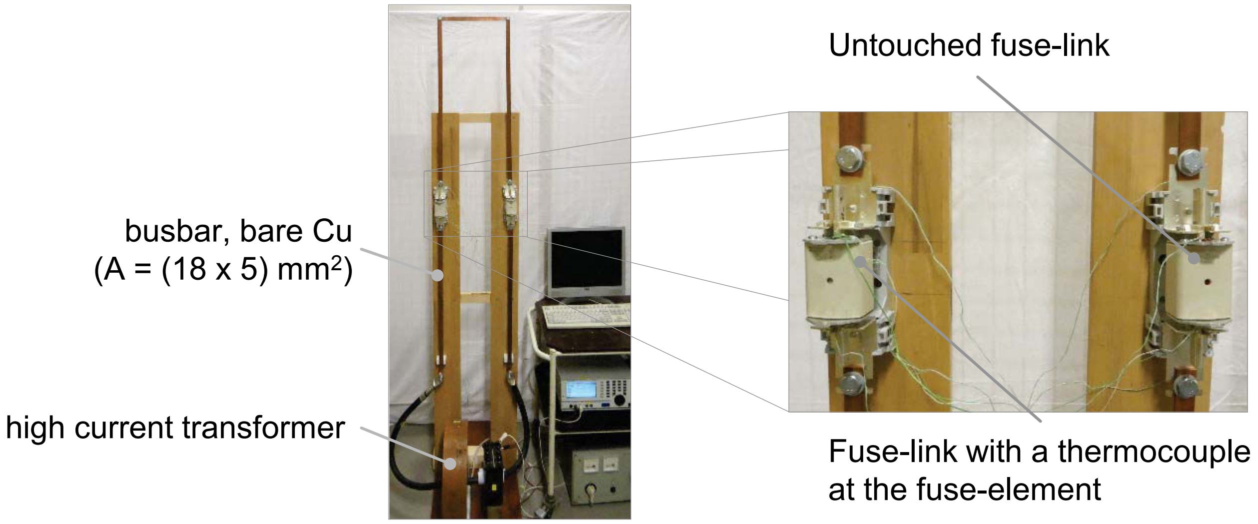
In contrast, fuse-elements with the solder of a SnBiCu alloy (type A) showed a deviant performance. In case of heat treatment at 160 °C, the resistance has been increased continuously from the beginning. In the range of 500 h till 1000 h the gradient decelerated and is staying nearly constant up to now. This curve progression corresponds with the typical growth kinetics of IMC layers, described by Fick's laws. The reaction speed of the interdiffusion slows down, since the concentration gradient at the interfaces are changing due to the growth of the IMCs. Because of the worse electrical conductivity of IMCs, available cross section is reduced and leads to an increasing resistant [3]. Furthermore, bismuth, which doesn't participate at the interdiffusion reaction between tin and copper, could be accumulated at the IMC-solder interface and might act as an additional barrier for the initial interdiffusion [7]. Starting fragmentation of the solder's surface could be observed moreover, which indicates relevant growth of oxide layers and a decrease of interdiffusion's reaction speed, since the remaining solder volume is reduced continuously. At the lower temperature of 140 °C the resistance stayed nearly constant at the first 1000 h and increases slowly afterwards. However, the reaction speed of interdiffusion is much lower than at 160 °C. But the readings indicate already, that the interdiffusion might not be negligible at this temperature.

Temperature gradient between fuse-elements and blade contact

Temperature rise tests with fuse-links containing the investigated fuse-elements from the long-term tests, were conducted to get an insight into the thermal stress of fuse-elements at normal operation. Thereby the temperature gradients between the blade contacts and the fuse-element have been measured to draw conclusions on the fuse-element's thermal stresses.

1_Experimental setup

The temperature rise tests were conducted in consideration of the standard testing procedure described in [8]. Three different fuse-links were investigated with the rated values already mentioned in Table 1. The fuse-links were installed in a common fuse base of the same size and were mounted on a special framework to enable a free-standing test setup. For measuring the fuse-element's maximum temperature, one fuse-link of each type was disassembled and a thermocouple was bonded at the solder deposited area. Therefore a special adhesive has been used, which is particular suitable for high temperatures. Afterwards the previously extracted silica sand was dried in an oven and the fuse-link was mounted once again. The electrical resistance of the fuse-link has been measured before, during and after the preparation for quality assurance. Thereby no changes could be detected. Additional thermocouples were mounted at the blade contacts and the connections of the fuse base. Therefore a hole has been drilled, in which the thermocouple was fixed by punching the adjacent material. A second fuse-link was prepared in the same way but without a thermocouple on the fuse-element for controlling the readings of the prepared one (Picture 5). Both fuse-links were connected in series by bare copper busbars with a cross-section of (18 x 5) mm^2. The current was applied with a high current transformer. Current load was varied between I = 50 A and I_r = 250 A and logged with a measuring system together with all temperatures.

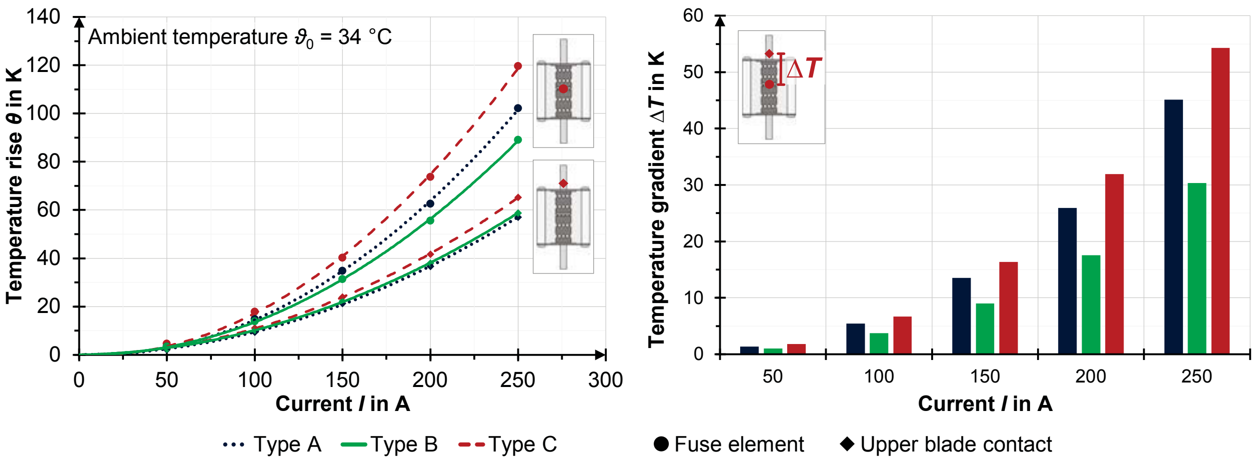


Picture 5: Experimental setup for temperature rise test of fuse-links at ambient conditions

2_Results and discussion

The temperature rises of the upper blade contacts and the maximum fuse-element temperatures are analyzed, since their temperature gradient is of special interest. The temperature rise of the connection between the fuse base and the busbar was about $\theta \approx (46 \ldots 51)$ K at rated current. This temperature rise is lower than the limiting temperature of bare copper contacts (Picture 2). Furthermore no significant differences between the readings of the blade contacts of prepared and untouched fuse-link were measured.

Although the tested fuse-links have the same rated values, they showed considerably different thermal characteristics (Picture 6). Indeed, with temperatures between 91 °C and 99 °C at rated current the blade contacts are not varying too much, but the temperature gradients and thus the maximum temperatures of the fuse-element at the solder deposited areas are significantly different (Picture 6, right). So the highest temperature gradient was reached by type C with about 54 K at rated current and the lowest by type B with 30 K. Taking into account the solder's melting temperature (Picture 2) and the initial results of the long-term tests (Picture 4) of these two types, there seem to be some "reserves" at maximum temperature and temperature gradient for more challenging conditions at higher thermal stresses. Type A has reached a maximum fuse-element temperature of 136 °C at rated current. Since the solder already starts melting at temperatures ≥ 165 °C (Picture 2) and increasing resistances have been measured during the long-term test at 160 °C (Picture 4) yet, this type of fuse-link might have a higher probability of accelerated ageing in case of higher thermal stresses than the other types.



Picture 6: Temperature rise of the fuse-elements and blade contacts (left) and the temperature gradient (right) depending on the current load

Conclusion and future research

Continuous development and changes of low-voltage grids, especially by the expansion of renewable energy, lead to higher requirements of NH-fuses. This causes increasing thermal stress of fuse-links and leads to an accelerated ageing of the fuse-elements. Interdiffusion and chemical reactions like oxidation have been identified, being the major ageing mechanisms, which lead to these failures. Long-term test were started with several common fuse-elements to investigate the consequences of these mechanisms on the operating behavior in detail. First readings indicate, that fuse-elements, containing solder with a high proportion of tin and in consequence a relatively high melting temperature, might be less susceptible to accelerated ageing. The long-term test will be continued to an operating time of at least 10.000 h and will be supplemented by additional current-loaded tests of fuse-elements under standard and inert atmosphere. In combination with tripping test of these aged fuse-elements and new fuse-elements, the influence of interdiffusion and of normally inseparably linked oxidation should be qualified separated from each other. Based on this results material-depending limiting temperatures of fuse-elements for a long-term stable operation can be specified.

First investigations of the thermal behavior of fuse-links, with identical rated values and containing the fuse-elements from the long-term tests, showed a considerably different heating of fuse-elements. That leads to varying thermal stresses at the same operating conditions and varying robustness in case of higher thermal stress, e. g. in encapsulated systems, too. Therefore, future investigations have the aim to investigate this thermal behavior while the fuse-links are installed in an encapsulated switchgear too and at varying ambient conditions. Based on these results, the temperature gradient between the blade contacts and the fuse-element should be calculated, depending on different operating conditions. Temperature gradient together with the material-depending limiting temperatures of fuse-elements enable us to recommend corresponding limiting temperatures for the blade contact as well, which might be easily measurable in practice and allow a long-term stable and reliable operation of fuse-links.

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