1. Anita LEŚNIAK[1], 2. Marcin SZEWCZYK[1], 3. Tadeusz DASZCZYŃSKI[1], 4. Piotr PIEKARSKI[2]

Warsaw University of Technology, Electrical Power Engineering Institute, Division of Power Apparatus, Protection and Control (1),
ABB Sp. z o.o. Technology Centre, Żegańska 1 St., 04-713 Warsaw, Poland (2)
ORCID: 2. 0000-0003-3699-5559; 3. 0000-0002-6262-0286

doi:10.15199/48.2025.01.08

Development tests and FEM simulations of maximum load characteristics of medium voltage fuse links

***Abstract**. This paper reports on development tests of the maximum load characteristics of medium voltage (MV) fuse links. The ABB motor fuse type CMF (Circuit Motor Fuse) rated at 12kV/200A was dismounted for testing of its link temperature while heating up with a rated current of 200 A. The tests were conducted for a link dismounted from a fuse and for the link mounted in a porcelain casing. The fuse casing containing the link had two options: filled with sand or left empty. While heating up, the temperature was measured on the fuse link in all cases. The tests were aimed at analyzing the impact of the environment on heat transfer from the fuse link to the environment. The tests were motivated by the adverse correlation between the overheating of the fuse links and the process of the fuse aging, which is a primary cause of their failures. The results reported so far are limited to examining the temperature at the fuse fittings and in the center of the porcelain casing. The research reported in this paper contributes to a better understanding of the behavior of the fuse links depending on the surrounding environment to which the heat is dissipated from the fuse links. A Finite Element Method (FEM) model was developed and qualitatively validated against the testing results. The model is suitable for allowing qualitative assessment of the fuse heating in an environment with limited heat exchange.*

***Streszczenie.** W artykule przedstawiono badania rozwojowe charakterystyk maksymalnego obciążenia wkładek bezpiecznikowych średniego napięcia (SN). Bezpiecznik silnikowy ABB typu CMF (Circuit Motor Fuse) o napięciu 12kV/200A został zdemontowany w celu sprawdzenia temperatury jego topika podczas nagrzewania prądem znamionowym 200 A. Badania przeprowadzono dla topika zdemontowanego z bezpiecznika oraz dla osadzonego w porcelanowej obudowie. Badania wykonano dla dwóch układów: bezpiecznik wypełniony piaskiem lub pusty. Podczas nagrzewania we wszystkich przypadkach mierzono temperaturę na wkładce bezpiecznikowej jak i topiku. Badania miały na celu analizę wpływu otoczenia na przenikanie ciepła z wkładki topikowej do otoczenia. Motywacją do przeprowadzenia badań była negatywna korelacja pomiędzy przegrzaniem wkładek bezpiecznikowych a procesem starzenia się bezpieczników, który jest pierwotną przyczyną ich awarii. Dotychczasowe wyniki ograniczają się do badania temperatury na obudowach bezpieczników i w środku porcelanowej obudowy. Badania przedstawione w tym artykule przyczyniają się do lepszego zrozumienia zachowania wkładek topikowych w zależności od otaczającego środowiska, do którego odprowadzane jest ciepło z wkładek topikowych. Opracowano model metody elementów skończonych (MES), który poddano walidacji jakościowej w oparciu o wyniki testów. Model umożliwia jakościową ocenę nagrzewania się bezpiecznika w środowisku o ograniczonej wymianie ciepła. (**Testy rozwojowe i symulacje FEM charakterystyk maksymalnego obciążenia wkładek bezpiecznikowych średniego napięcia**)*

Keywords: fuse links, MV fuse, FEM, modeling and simulation.
Słowa kluczowe: wkładki bezpiecznikowe, bezpieczniki SN, FEM, modelowanie i symulacja.

Introduction

A fuse is a power system component that performs the function of conducting operating current and switching off overcurrent or fault current, in particular short-circuit current. The fuses are much needed components in modern power system despite of their relatively straightforward operational principle. They operate along with much more complex devices, such as motors, transformers, capacitor banks, energy sources, automation equipment of industrial facilities, or power electronics converters of modern grids. Reliable operation of fuses contributes to the safety, reduced down-time, and improvement of the overall system performance.

When the current exceeds a certain value, the fuse blows, thus thermally (or electrically) interrupting the electrical circuit. In the case of high instantaneous current values, in some electrical circuits the fuse may melt and vaporize so quickly that its failure may result in limiting the current value. As the main function of fuses is to protect power equipment against fault currents, fuses are reliable in interrupting fault currents but may face challenges when operating in the overcurrent range. The over-current conditions include currents 2-8 times as high as the rated current, so these are currents with a value much lower than typical short-circuit current values [1]. This paper aims at investigating fuse links operation in overcurrent conditions.

In the era of rapid power engineering technology development, there is an in-creasing demand for accurate and comprehensive testing techniques to ensure the effectiveness and reliability of medium voltage (MV) fuse links. The complexity of electrical systems and the variety of applications they serve require an understanding of how medium voltage fuses respond to operating conditions. Testing methods are often time-consuming and costly, and they may not provide a complete picture of the fuse link's performance in particular conditions. As a result, carefully conducted measurement tests are indispensable in the design and optimization of medium voltage fuse links.

This article explores the latest developments in the field, including the challenges faced by engineers and researchers when evaluating medium voltage fuses, the tools available to investigate their maximum load characteristics, and the role of field simulations in predicting the fuse links behavior under various conditions.

The subject of this publication is a measurement of the maximum load characteristics of medium voltage fuse links. In the studies reported so far on the subject, the temperature of the fuse link inside the fuse was not tested. Measurements here reported were performed in a system of dismounted fuse link, in which the fuse link was used without sand and with sand.

Fuse testing

Electric current flowing through any conductor produces thermal energy. The higher the current value and the higher resistance of the conductor, the higher the energy value dissipated in the conductor (1):

(1) $$P = I^2 \times R$$

where P is the power dissipated per unit length (W), I is the current in the conductor (A), and R is the resistance per unit length of the conductor (Ω).

The thermal steady state condition (long-term load capacity) is a state in which the conductor has reached a steady temperature ϑ_u as a result of the current flow of a constant value I_u,. In such conditions all of the Joule heat (2) released in the conductor is transferred to the neighbouring environment:

(2) $$dQ = R(\vartheta, k_w) i(t)^2 dt$$

where: $R(\vartheta, k_w)$ is the resistance of the elementary section of the current path with resistivity $\rho = f(\vartheta)$, S is cross-sectional and dl is elementary length of the conductor. The resistance in (2) depends on the temperature and the degree of use of the conductor cross-section by the current flow kw. The relationship between the steady current I_u and the steady temperature ϑ_u of the conductor [2] is as follows (3):

(3) $$I_u^2 = a(\vartheta_u - \vartheta_0) = a\tau_u$$

where: a is a constant value in the working temperature range, depending on the material properties of the conductor, its size, and conditions of the heat dissipation to the environment, ϑ_0 is a standardized ambient temperature, and τ_u is a steady temperature increase.

The research reported so far was limited only to examining the temperature at the fuse fittings (mainly for low voltage applications) and in the middle of the porcelain casing during heating [3-5]. These are tests that the manufacturer requires to conduct for different fuses, depending on their type, to check temperature increases in different locations along the fuse, in accordance with the IEC Std. 60282-1 [6]. These temperatures are usually tested for 30% and 60% of the rated current, and in some cases also for 100% of the rated current. The effect of the heat convection is required to be included in the examination in the case when the fuse is intended to operate in a vertical position or in the case when the fuse is intended to operate in an environment with limited heat ex-change. However, testing of the temperature at the fuse link inside the fuse, as reported in this paper, has not been published so far. Measuring the temperature directly on the fuse casing does not accurately reflect the actual temperature of the fuse link located inside the casing.

Another important aspect that has not been investigated either is how enclosing the fuse in canisters inside MV (gas) switchboards affects the overheating of the fuse link. An environment with limited heat exchange means that the ventilation of the fuse is limited during its operation (heating). As a result, the fuse overheats much faster, which may result in the fuse burning out not in accordance with its characteristics. In such a case it is also more likely that the fuse will degrade in a short time, and that the fuse will need to be replaced frequently with a new one. This is specifically the case for the fuses made of copper or other commodity materials, while the fuses made of, e.g., silver are not subject to degradation due to a long-term high temperature. When fuses are placed in canisters, the manufacturer recommends reducing the current flowing through the fuse link during its operation to 75% of the rated current. However, this is a rough estimation against which this work provides measurement data and new in-sights. This implies that the specific arrangement of the fuse during testing, as reported in this paper, should be considered when selecting the fuse insert for a medium-voltage gas-insulated switchgear. It also suggests oversizing the fuse depending on the heat transfer conditions of the switchgear equipment with which the fuse is installed [7].

Research published so far on fuses reports on how the fuse fittings affect the temperature of the fuse [8], what temperature increase is expected at the fittings and at the locations other than the fittings [9]. A mathematical method (e.g. [10]) for calculating these temperatures depending on the design, dimensions, and the use of the fuse insert allows to obtain the temperature difference between the middle of the fuse casing and the fuse fittings, which is several degrees Celsius. It is thus feasible to calculate the temperature at the fuse casing and at the fuse fittings for individual inserts, the heat transfer conditions from the fuse links to the fuse casing, and for the fuse operating conditions (conducting current). However, calculating temperature of the fuse requires design sketches of the fuse and a large amount of measurement data. Extensive measurement campaigns can be replaced or supported with a computationally reliable numerical models of the fuse.

With this respect, there are publications on using Finite Element Method (FEM) analysis for thermal investigation of the fuses [11-16]. Identification of the thermal parameters for the high-breaking capacity of low-voltage fuses was described, e.g., in [17] where Differential Evolution algorithm was compared with the measurements and the calculated 3D model. In this paper, we report on a FEM model of a fuse link that enables qualitative evaluation of the temperature at the link during heating.

Test set-up and initial testing arrangement

The test set-up was first established, as shown in Fig. 1, with the arrangement of the fuse under test. The initial observations included how the fuse behaves when heated with different current values and what the temperature is in different locations on the fuse casing surface. The experience gained during the initial tests helped to establish the heating procedure used for the fuse link mounted on a plastic bracket (Fig. 2) without additional fixtures for the current value of 150 A (Fig. 3) and 200 A (Fig. 4), and for fuse link mounted in the fuse fittings in porcelain casing filled with sand (Fig. 6).

According to the IEC Std. 60282-1 [6], measurement conditions met the following requirements:

- maximum ambient temperature was 40°C and its average value measured over the last 24 hours did not exceed 35°C;
- height did not exceed 1000 m;
- the ambient air was not polluted by, e.g., dust, smoke, flammable gases, or corro-sive substances;
- vibrations caused by external sources were negligible or non-existent.

Fuse links of a given type were selected for testing, with the highest possible rated current available for each size and type of fuse. The tests were performed in a closed laboratory that was free from heat sources other than the tested fuse. Uninsulated copper wires, each approximately 1 meter long, were used to comply with the recom-mended connections of the fuse to the test circuit under given testing conditions.

The temperature of the various parts of the fuse was determined by thermocouples, placed and protected in a way that ensured good heat conduction. The temperature rise was recorded at regular intervals during testing. The temperature of a given element was measured by attaching a thermocouple to the surface of that element.

The measurement system consisted of the following components (Fig. 1):

- AT: autotransformer METREL HSN 260/30 M500 (Up = 230V, Us = 0-260V, Is = 30A, P = 7.8 KVA),
- T: transformer ET1o-1,9 (S = 1.9 kVA, Uk = 3.45%, U1 = 260V, U2 = 15/2.0V, I1 = 7.68A, I2 = 60/500A),
- PP – current transformer ISWb 200/5 (S = 5VA, FS5, cl. 0.2S, 200/5 A/A),
- OB – examined object,
- A – ammeter Agilent 34972A,
- V – voltmeter HIOKI 3332.

The connection of the tested fuse to the measurement system differed depending on the stage of testing. The fuse itself was placed on the support and was connected to the testing system using double copper tape. The ferruled fuses were placed on special fuse bases. For the measurements of the sole fuses, the fuses were located in the switch housing. To provide connection, two copper wires with a cross-section of 240 mm2 on each side were used. The ambient temperature was measured using a thermocouple placed in oil to make the measurement less susceptible to interference from ambient environment.

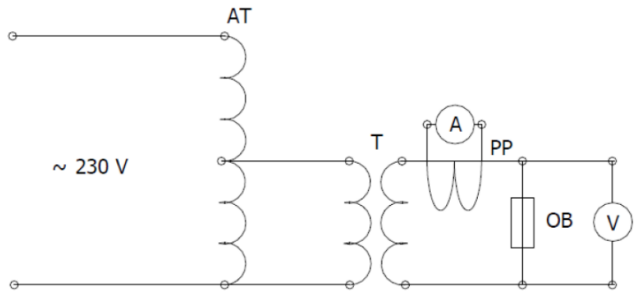


Fig.1. Single line diagram of the measurement system used for heat testing of fuse links (see Fig. 2) and fuses (see Fig. 5); AT: autotransformer METREL HSN 260/30 M500, T: trans-former ET1o-1.9, PP – current transformer ISWb 200/5, OB – examined object, A – am-meter Agilent 34972A, V – voltmeter HIOKI 3332.

The fuse link tested was taken from the dismounted CMF (Circuit Motor Fuse) type motor fuse from ABB [7]. The serial number of the fuse was 000942, and its rated current was 200 A. The internal resistance of the fuse was measured prior to measurements, as 2.86 mΩ. Agilent BenchLink Data Logger 3 was used to record the measurement data from heating tests.

Fig. 2 shows a fuse link wound on a plastic bracket from CMF fuse type. The thermocouples are glued symmetrically on the opposite sides of the link. Two of the thermocouples are located at one-quarter of the length (1 and 2 channels in Fig. 3, 4 and Table 1) and the other two are located at half the length of the link (3 and 4 in Fig. 3, 4 and Table 1). Thermocouples were placed at the same distance in pairs with the following considerations:

- in the middle of the carrier, two thermocouples, one in direct contact with the fuse, and in the other we leave a minimal air gap (the thermocouple almost touches the fuse). These two thermocouples are placed opposite each other, halfway along the length of the fuse.
- in one fourth of the length of the carrier – similarly as above.

Measurements started with 150 A (75% of the insert's rated current) as the reference current value for each system. This current value was selected conventionally on the basis of the assumption that the fuse would not burn out during the first measurement. This measurement continued until the temperature stabilized, which is a procedure in accordance with the IEC Std. 60282-1 [6]. Once the temperature was established for the initial current value, the current was increased to the rated value of 200 A, but at this point, it was assumed that 180°C would not be exceeded. Therefore, it was feasible to heat the tested component up to the rated current, but when this temperature limit was exceeded, the system was turned off.

The contact point of each thermocouple was checked using auxiliary wires with a galvanic connection to the thermocouple. In this system, during the measurements, each thermocouple was in contact with the fuse.

a)

b)

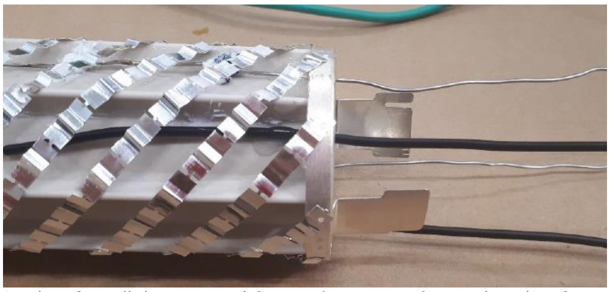


Fig.2. a) A fuse link prepared for testing, wound on a bracket from tested CMF fuse; the thermocouples are glued symmetrically on the opposite sides of the link (two of them located at half the length of the link, the other two located at one-quarter of the link).
b) Thermocouple placement method.

Temperature stabilization at each measurement point occurred after 3 hours and 40 minutes of heating the fuse link with a current of 150 A, which is in accordance with the IEC Std. 60282-1 [6]. The heating process for a test with a current of 150 A is shown in Fig. 3. The heating process for the heating test (the fuse itself on the bracket) for bracket no 000942 is shown in Fig. 4.

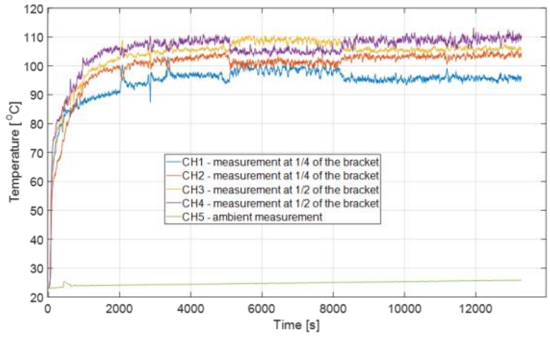


Fig.3. The course of the heating for fuse link on a bracket (shown in Fig. 2) for a test with a current of 150 A. The long-term current was set to 150 A; heating was continued until the temperature increase measured by each thermocouple was less than 1 K for an hour, with a total measurement duration of 3 hours and 40 minutes.

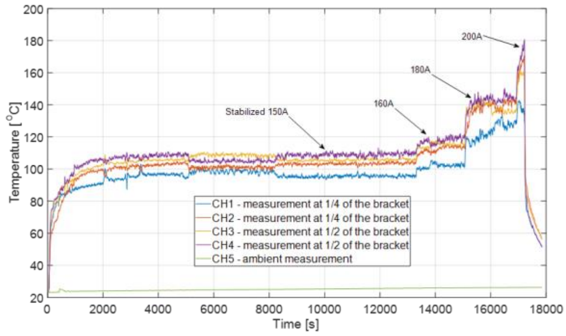


Fig.4. The course of the heating for fuse link on a bracket (shown in Fig. 2) for a test with a current of 180 A. The long-term current was set to 180 A; heating was continued until the temperature increase measured by each thermocouple reached 180°C.

Tests of the complete fuse comprising of the fuse link, fittings, and porcelain casing

After completing the test of heating the sole fuse link mounted on a plastic bracket, as described above, and after allowing it to cool down, the fuse link on the bracket was then attached to the fittings of a fuse housed within a porcelain casing (Fig. 5). The galvanic connection was subsequently verified for each thermocouple, employing a separate wire connected to the thermocouple, insulated, and led outside of the porcelain casing.

The heating tests were conducted under two conditions of heat transfer from the fuse link to the fuse casing: the first condition involved no sand inside the fuse casing, while the second condition involved sand being present inside the casing. The heating test for the fuse without sand was performed for a reference current value of 150 A. After 30 minutes (in the 44th minute of the test) from setting the current to 150 A, the temperature for the thermocouple placed at the middle of the bracket reached 180°C. These values were used as a reference for the follow-up tests.

In the next step, the fuse casing was filled with sand in a manner ensuring proper heat dissipation from the fuse link. The contact of each thermocouple with the fuse link was checked using a measuring device, probing the thermocouple resistance. The test setup is shown in Fig. 5.

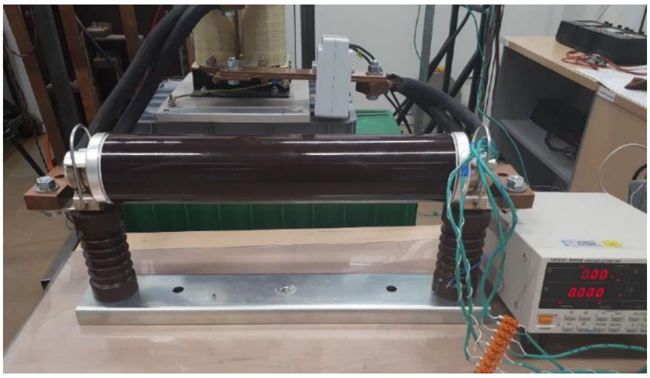


Fig.5. Test setup used for heat testing of fuse links mounted inside the fuse porcelain casing and the fuse mounted to the fittings; thermocouples are attached to the fuse link and led outside the fuse casing.

The test started with a current value of 130 A and then remained at this value until the temperature was determined in accordance with the IEC Std. 60282-1 [6]. Subse-quently, the current value was increased to 150 A (as in the case without sand) and up to the rated current of 200 A. After 5 hours and 5 minutes of heating, the temperature for each measuring point stabilized for the current value of 130 A, and the current was then increased. The next day, a heating test with a current of 200 A was started. After ap-proximately 6 hours of heating, the temperature at each measurement points stabilized, in accordance with the IEC Std. 60282-1 [6]. Table 1 shows the results of the measured temperatures for each current value at steady state conditions. Fig. 6 shows a heating test results with a current of 200 A.

	Ch 1 [°C]	Ch 2 [°C]	Ch 3 [°C]	Ch 4 [°C]	Ch 5 [°C]
Temperature stabilization for 130 A	84,09	83,57	86,27	85,66	25,63
Temperature stabilization for 150 A	104,21	102,92	106,92	105,70	25,75
Temperature stabilization for 200 A	171,59	168,08	176,29	172,80	24,19

It should be noted that the fuse link breaks at a temperature of approximately 250°C due to the melting point of tin, which is used as the fuse link material. Therefore, we ensured that the temperature did not exceed 200°C. In the centre of the fuse link there is a point made of tin, which is intended to ensure that the fuse link breaks faster if the temperature surpasses a certain threshold.

When heating the fuse on the support (see Fig. 5), surrounded only by free air and without any measures to control environmental conditions, the system is unstable in terms of heat dissipation (turbulence of the cooling air flow), any flow of the free air causes disturbances in the measurement conditions. The point of contact between the thermocouples and the fuse link, the force with which it presses against the fuse, and the distance from the support arm to the fuse (since the support to some extent also absorbs the heat), all impact the measurement results and are unique to each test configuration.

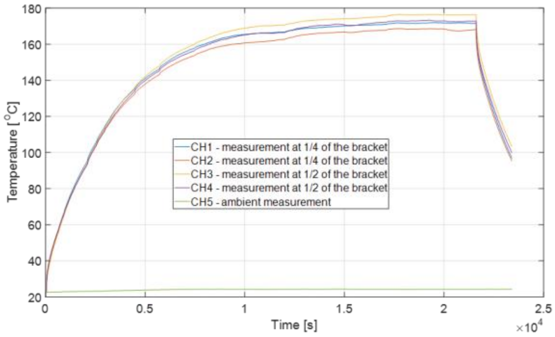


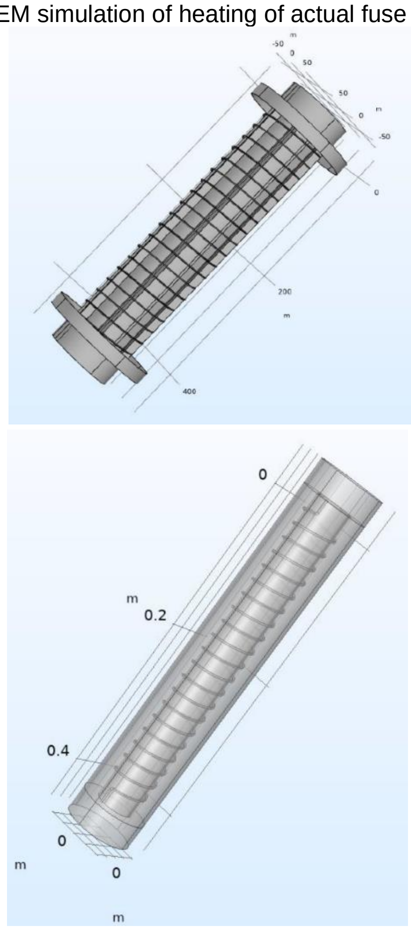
Fig.6. Heating test with a current of 200 A for the complete fuse link (Fig. 5).

FEM model for evaluation of fuse temperature

This section aims to describe a numerical model of the fuse and the simulation results of the process of heating up and heat release during the fuse heating test. The model was developed using the COMSOL Multiphysics simulation software [18], which allows for qualitative examination of potential changes and their effects in the design of the fuse links, thereby enhancing understanding of their operational parameters.

In the first step, a model of the medium voltage fuse link shown in Fig. 2 was supplemented with the mounting parts of the actual design as shown in Fig. 5. The de-sign drawings (Fig. 7a) were adapted (Fig. 7b) to reproduce critical parts for FEM simulation of heating of actual fuse link.

a)



b)

Fig.7. FEM model of the fuse link: a) design drawing, b) model adopted for FEM heating simulations.

After determining the geometry of the fuse link, which was based on the actual dimensions of the previously tested CMF fuse links (Fig. 5), the material parameters were assigned, for copper, sand, silver, and ceramics parts, surrounded with air. The fuse insert fittings were modeled with copper material, the fuse link was modeled with silver, the fuse support with ceramic, the space around the fuse link was modeled as sand, and the surroundings were modeled as air. The boundary condition of temperature type was set with the temperature value set to 25°C, representing the temperature of the ambient air surrounding the investigated geometry.

The resultant temperature distributions along the fuse link and the surroundings were strongly dependent upon the fuse ventilation, represented by the air surrounding the fuse insert and its temperature. The maximum temperature of the fuse and fittings was affected by how closely the boundary condition indicating room temperature was determined. The room temperature was simulated few cm from the heated fuse tube. In this space, the air is heated by the heated fuse, mainly due to thermal radiation.

The heat source was represented by the heat flux. The power it generated during heating with the rated current was specified by the manufacturer as 166 W. All other elements of the fuse were defined as elements that were not a source of heat.

The results show that the fuse element has the highest temperature in the midway through its length and is approximately 470 K, or 196.85°C (Fig. 8a).

a)
b)

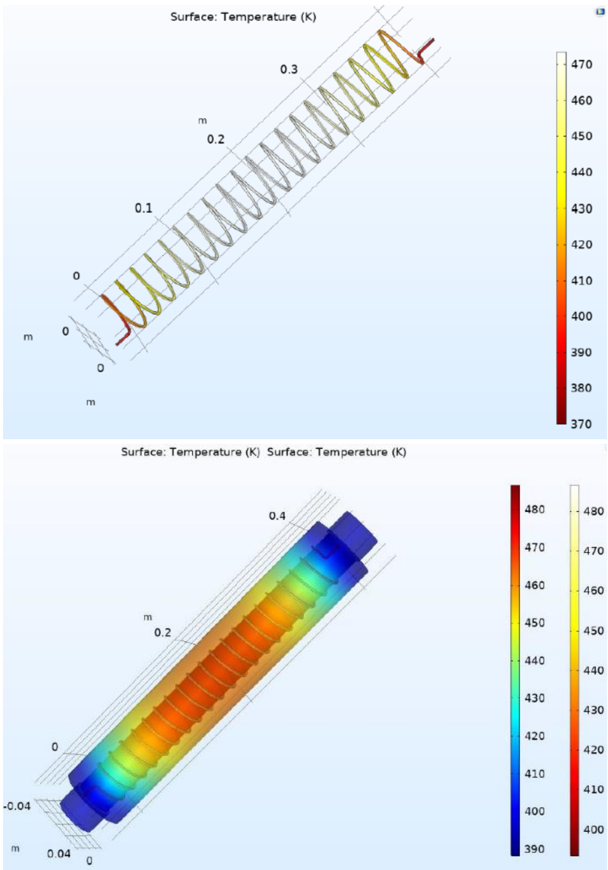


Fig.8. a) Temperature at the fuse link, b) temperature at the fuse insert after adding a porcelain tube to the model – FEM simulation results.

Fig. 8b shows the FEM simulation results and the temperature distributions at the fuse link after adding the porcelain tube to the model. Adding a porcelain tube affects the temperature only slightly: the maximum temperature is then decreased by 10 K.

The temperatures simulated during the fuse heating test closely match those obtained from the measurements. The maximum temperatures obtained from simulations are only slightly higher than those obtained from the measurements. The maximum temperature calculated with the simulation model was 206.85°C on the fuse, and 116.85°C on the fittings. These values are in good agreement with the temperature obtained from the measurements, where the temperature on the fuse reached values of approximately 190°C (9% discrepancy). The model developed allows to qualitatively evaluate the effect of the heat dissipation conditions on the maximum temperature during testing. This can be specifically useful when evaluating heating performance of the fuse link sealed in an environment with a limited heat exchange capacity. Another observation is the necessary and adequate level of model complexity required to achieve a qualitatively accurate reproduction of the measurement results for fuse heating tests.

Conclusions

Reliable and efficient delivery of electrical power all the way from generation to end customers is a fundamental requirement of modern societies. Medium voltage fuses, along with other critical components, play a vital role in protecting electrical systems and power components from overcurrent and faults, which is essential to en-sure reliable and uninterrupted power supply. These components, although relatively simple in principle, are carefully designed to disconnect a circuit in the event of exces-sive current, preventing damage to equipment and ensuring safety of both the system and its operators.

The study reports on development tests of the maximum load characteristics of medium voltage fuse links with various heat dissipation conditions. The experiments were carried out on a link that was removed from a fuse and a link that was housed within a porcelain casing without sand and filled with sand. A procedure was presented for preparing the fuse link for measurements, with effective placement of both the fuse link itself and the thermocouples along the fuse link. The temperature on the fuse link in selected locations inside the fuse was studied for a commercial 12kV/200A motor fuse type CMF. A Finite Element Method (FEM) simulation model of the fuse was also proposed allowing to qualitatively evaluate the fuse heating with various heat exchange conditions to environment. The model yielded temperature results that closely matched those obtained in measurements, demonstrating the required level of complexity for accurately reproduce the outcomes of fuse heating tests.

For a fuse link that is not yet fastened and covered with sand, the key factors con-tributing to the temperature distribution along the fuse link are the point of contact between the thermocouple and the fuse link (what surface they touch). Other critical factors include: the force with which the thermocouple presses against the fuse and the distance from the support arm (which is practically unfeasible to control).

After fitting the fuse link with the fuse fittings, the situation becomes more stable due to the presence of additional elements in the form of fittings that facilitate heat dissipation. For the fuse link mounted to fuse fittings and enclosed in the fuse casing filled with sand, it is evident that the heat spreads from the inside to the outside of the insert. This is manifested with the lower temperature of the thermocouples at 1/4 of the fuse link length than the temperature at 1/2 of the fuse link length (Fig. 6). The temperatures measured and simulated indicate that when the fuse links are heated with the rated current, their temperature does not exceed 180°C for the time of the heating test (Fig. 6 and Fig. 9).

The research reported may be useful for investigating the heating performance of the fuse link when sealed in an environment with limited heat exchange capacity. From a design and product perspective, such investigations can be useful for avoiding over-sizing of the fuses in environments with limited heat exchange capacity and for the effective planning the time- and cost-consuming heat testing of equipment. The simulation model described can aid in identifying design modifications and contribute to the development of a test plan.

Acknowledgments: The authors would like to thank Prof. Jacek Starzyński from Warsaw University of Technology for providing support to COMSOL Multiphysics simulations and for Mr. Dariusz Glina from Hitachi Energy for help in working on the physical model.

***Authors**: mgr inż. Anita Leśniak, Politechnika Warszawska, Instytut Elektroenergetyki, ul. Koszykowa 75, 00-662 Warszawa, E-mail: anita.lesniak.stud@pw.edu.pl; dr hab. inż. Marcin Szewczyk, Politechnika Warszawska, Instytut Elektroenergetyki, ul. Koszykowa 75, 00-662 Warszawa, E-mail: marcim.szewczyk@pw.edu.pl; dr inż. Tadeusz Daszczyński, Politechnika Warszawska, Instytut Elektroenergetyki, ul. Koszykowa 75, 00-662 Warszawa, E-mail: tadeusz.daszczynski@pw.edu.pl, mgr inż. Piotr Piekarski, ABB Sp. z o.o. Technology Centre, ul. Żegańska 1 St., 04-713 Warszawa, E-mail: piotr.piekarski@pl.abb.com.*

REFERENCES

[1] 1. Wright, A., & Newbery, P. G. (2004). Electric fuses (Vol. 49). IET.

[2] J. Maksymiuk, J. Nowicki, “Aparaty elektryczne i rozdzielnice wysokich i średnich napieć”, Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw 2014

[3] C. D. Halevidis, P. I. Mouzakitis, A. D. Polykrati and P. D. Bourkas, "The effect of the fuse enclosure temperature rise on low voltage overhead conductor protection," MedPower 2014, Athens, 2014, pp. 1-5, doi: 10.1049/cp.2014.1700

[4] Baraboi, A., Ciutea, I., Adam, M., Pancu, C., & Baraboi, T. A. (1999). Modelling and simulation of the thermal stress at the electric fuses contacts. In 6th International Conference on Electrical Fuses and their Applications (pp. 59-64).

[5] C. Kühnel, S. Schlegel and S. Großmann, "Investigations on the long-term behavior and switching function of fuse-elements for NH-fuse-links (gG) at higher thermal stress", Proc. 6th Int. Youth Conf. Energy (IYCE), pp. 1-8, Jun. 2017

[6] IEC 60282-1:2020 High-voltage fuses - Part 1: Current-limiting fuses

[7] ABB Sp. z o.o. Medium-voltage fuses. https://search.abb.com/library/Download.aspx?DocumentID=2401PL1613-W1-en&LanguageCode=en&DocumentPartId=&Action=Launch

[8] Conference papers Electric fuses and their applications, Liverpool Polytechnic, ICEFA, 1976

[9] 6th Conference on electric fuses and their applications, Torino, ICEFA, 1987. ISBN 88-900352-1-8

[10] 3rd international conference on electrical fuses and their applications, Eindhoven, ICEFA, 1976. ISBN 90-6144-966-0

[11] Farahani, H.F.; Asadi, M.; Kazemi, A. Analysis of thermal behavior of power system fuse using finite element method. In Proceedings of the 2010 4th International Power Engineering and Optimization Conference (PEOCO), Shah Alam, Malaysia, 23–24 June 2010; pp. 189–195

[12] A. Plesca, "A complete 3D thermal model for fast fuses," 2007 8th International Conference on Electric Fuses and their Applications, Ceyrat, France, 2007, pp. 79-85, doi: 10.1109/ICEFA.2007.4419971

[13] H. Kürschner, A. Ehrhardt and G. Nutsch, "Calculation of prearcing times using the Finite Element Method", Proc. of the 5th ICEFA, pp. 156-161, 1995

[14] K. Jakubiuk, W. Aftyka, "Heating of fuse-elements in transient and steady-state", Proc. of the 7th ICEFA, pp. 181-187, 2003

[15] G. Chiriac, "Thermal analysis of fuses with variable cross-section fuselinks", Electr. Power Syst. Res., vol. 92, pp. 73-80, Nov. 2012

[16] M. Sarajlić, M. Hribernik, P. Kitak and J. Pihler, "Identification of the Thermal Parameters for the NH gG Fuse Using the Differential Evolution," in IEEE Access, vol. 7, pp. 55640-55648, 2019, doi: 10.1109/ACCESS.2019.2913553

[17] Szulborski, M.; Łapczyński, S.; Kolimas, Ł.; Kozarek, Ł.; Rasolomampionona, D.D.; Żelaziński, T.; Smolarczyk, A. Transient Thermal Analysis of NH000 gG 100A Fuse Link Employing Finite Element Method. Energies 2021, 14, 1421. https://doi.org/10.3390/en14051421

[18] Fanny Griesmer Joule Heating Simulations Tutorial, Jan 29, 2012, COMSOL Multiphysics.