LV Melting Fuse Convection Factor Calculation using an Optimization Algorithm

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***Abstract*—The article describes a method for the convection factor calculation for a low voltage melting fuse. The authors used a numerical and real model of the fuse. The numerical model is designed as a 3D model using the Finite Element Method, and includes material's temperature characteristics and boundary condition values. The real model presents the fuse, on which were mounted thermoelements to measure the temperature in laboratory conditions under nominal current 400 A. The optimization algorithm Differential Evolution (DE) was used to identify the convection factor in order to achieve minimum difference of the temperatures between the two models. Measured and model-calculated fuse temperatures are compared, and the agreement is satisfying which makes the fuse model relevant and suitable for the calculation of the fuse temperature.**

***Keywords*--convection factor identification, fuse link, low voltage, melting fuse, optimization, temperature**

I. INTRODUCTION

Electric fuse is a protection element, used in all power system applications. Current interruption opens the electric circuit during an excess of a determined value at the appropriate time [1]–[3]. Fuse's main task is protection of electrical devices, installations and people.

This article deals with the low voltage (LV) melting fuse, planned for installation in LV grid, up to 500 V (Fig. 1). It consists electrically conductive and non-conductive parts. Electrically conductive parts of the fuse are fuse contacts and fuse links. Electrically non-conductive parts of the fuse are ceramic body and quartz sand. Ceramic body must have good electric insulation material, and usually it is put up from steatite. Fuse contacts connect the fuse with electric circuit. The ceramic body is filled with the quartz sand, which extinguishes electric arc. The discussed fuse has 4 fuse links.

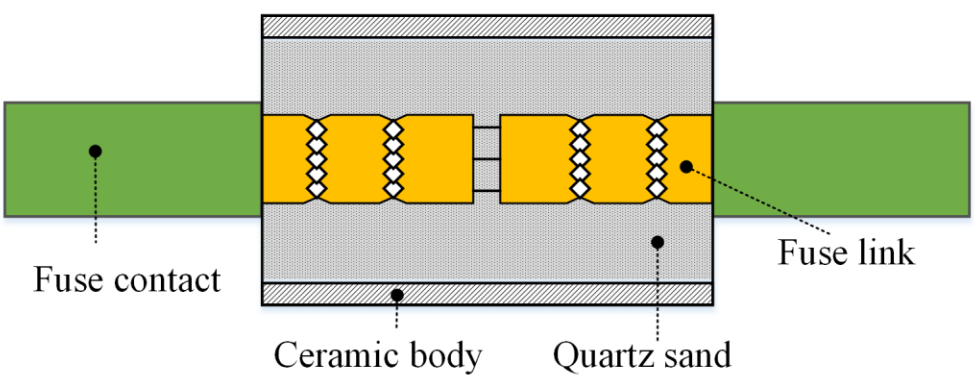

Figure 1. LV melting fuse

II. Temperature measurements

Temperature measurements were carried out in a testing laboratory at the Faculty of electrical engineering and computer science, University of Maribor. Temperature measurements were conducted using thermoelements (TE), which were placed to different locations on the outside and inside the fuse. They were located on:

- The top and the bottom of the upper fuse contact (TE_1, TE_2),
- The top and the bottom of the lower fuse contact (TE_3, TE_4),
- The upper and lower cover of the fuse (TE_5, TE_6),
- The ceramic body (the side with the inscription, the rear and the ride side) (TE_7, TE_8, TE_9),
- The fuse links (TE_{10}, TE_{11}, TE_{12}, TE_{13}),
- In the quartz sand inside the fuse (TE_{14}).

Temperature measurements were carried out by Joule heating the fuse under the nominal current 400 A. Table I shows the values of measured temperatures. Fuse links have the highest temperature (TE_{10}–TE_{13}, 125.3–134.4 °C).

TABLE I. MEASURED TEMPERATURES

Thermoelement	TE_1	TE_2	TE_3	TE_4	TE_5	TE_6	TE_7	TE_8	TE_9	TE_{10}	TE_{11}	TE_{12}	TE_{13}	TE_{14}
Temperature [°C]	81.3	92.5	81.9	94.2	86.5	83.7	76.5	83.7	85.9	125.3	134.1	134.4	131.2	88.9

III. Simulation model of the fuse

The fuse simulation model is designed a 3D model using the Finite Element Method (FEM) [4]. Fig. 2 shows a 3D model of a melting fuse, where the green color represents the fuse contacts and gray displays the ceramic body. Fig. 3 shows the fuse model without ceramic body, where the fuse links are shown in yellow. Material's electric and thermal properties of geometric shapes are shown in Table II. Simulation model has the following geometric shapes: fuse contacts, ceramic body, fuse link, quartz sand and surrounding (air).

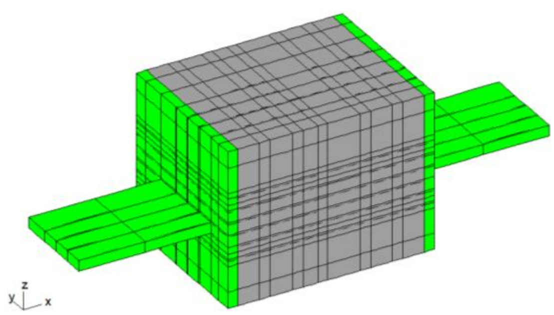

Figure 2. 3D model of a fuse, where green repsresntes the fuse contacts and gray displays the ceramic body

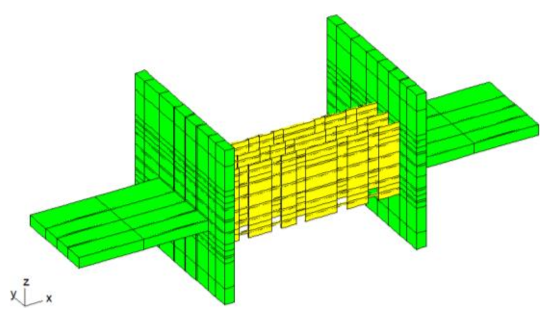

Figure 3. 3D model of a fuse, without the ceramic body (yellow represents the fuse links)

TABLE II. MATERIAL'S ELECTRIC AND THERMAL PROPERTIES [5]–[7]

Geometric shape	Electric conductivity [S/m]	Thermal conductivity [W/m·K]	Convection factor [W/m²·K]
Fuse contacts	$11 \cdot 10^{6}$	237	8
Ceramic body	$1 \cdot 10^{-9}$	2.5	7.5
Fuse links	$57 \cdot 10^{6}$	401	
Quartz sand	$1 \cdot 10^{-9}$	1	
Air	$1 \cdot 10^{-9}$	0.0257	

The fuse model is designed as a coupled problem that uses electric and thermal models. Electric model calculates the current density and electric conductivity, serving as the input data for the calculation of power losses. Thermal model uses the values of power losses for the calculation of temperature. Other input data for calculation of the temperature are materials electric and thermal properties from Table II. Those are the catalogue parameters, used for the numerical analysis of temperature. Surrounding area was defined as air with temperature as measured in the laboratory (25 °C). The calculated values of the fuse temperatures using catalogue parameters are shown in Table III, which are compared with the measured temperatures. The presence of deviations, between the measured and calculated temperatures, could be seen in Table III, which should be reduced as to improve the precision of the fuse simulation model. Section IV describes the optimization procedure, used to calculate the values of parameters for convection factor.

TABLE III. MEASURED (T_{MEAS}) AND CALCULATED (T_{CALC}) TEMPERATURES OF THE FUSE

Thermoelement	TE_1	TE_2	TE_3	TE_4	TE_5	TE_6	TE_7	TE_8	TE_9	TE_{10}	TE_{11}	TE_{12}	TE_{13}	TE_{14}
T_{meas} **[°C]**	81.3	92.5	81.9	94.2	86.5	83.7	76.5	83.7	85.9	125.3	134.1	134.4	131.2	88.9
T_{calc} **[°C]**	108.4	109.2	108.4	109.2	108.1	108.9	110.2	109.9	109.5	109.2	120.4	117.1	123.8	124.1

IV. CALCULATION OF THE CONVECTION FACTOR USING DE

This paper conducted the calculation of the convection factor using differential evolution (DE). DE is a fast and robust stochastic optimization algorithm [8]–[11], firstly introduced by Storn and Price [8], [9]. It is simple and effective algorithm, applicable for solving nonlinear optimization problems [10]–[11]. Detailed descriptions of this algorithm are available in [8] and [9].

There were 2 parameters to be calculated: convection factor of fuse contacts (p_1) and ceramic body (p_2). Fig. 4 shows the optimization process' flow diagram.

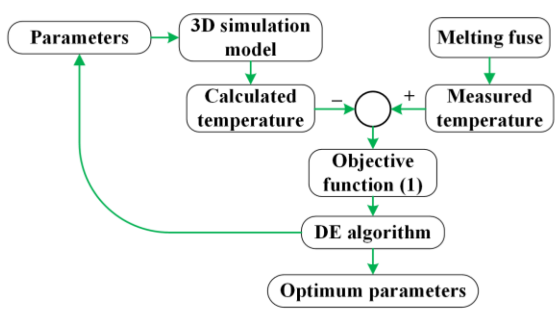

Figure 4. Optimization process' flow diagram

Population size was 40, weighting factor was 0.7, crossover constant was 0.5 and maximum number of iterations was set to 250. DE was minimizing the value of the objective function *OF* (1) through the optimization process:

$$OF = \sum_{i=1}^{7} OF_i \ , \qquad (1)$$

where OF_i, $i = [1,\ldots,6]$ are partial objective functions, written as:

$$OF_1 = \frac{\sqrt{(\mathrm{TE}_{1\_meas} - \mathrm{TE}_{1\_calc})^2} + \sqrt{(\mathrm{TE}_{2\_meas} - \mathrm{TE}_{2\_calc})^2}}{2}, \quad (2)$$

$$OF_2 = \frac{\sqrt{(\mathrm{TE}_{3\_meas} - \mathrm{TE}_{3\_calc})^2} + \sqrt{(\mathrm{TE}_{4\_meas} - \mathrm{TE}_{4\_calc})^2}}{2}, \quad (3)$$

$$OF_3 = \frac{\sqrt{(\mathrm{TE}_{5\_meas} - \mathrm{TE}_{5\_calc})^2} + \sqrt{(\mathrm{TE}_{6\_meas} - \mathrm{TE}_{6\_calc})^2}}{2}, \quad (4)$$

$$OF_4 = \frac{\sqrt{(\mathrm{TE}_{7\_meas} - \mathrm{TE}_{7\_calc})^2} + \sqrt{(\mathrm{TE}_{8\_meas} - \mathrm{TE}_{8\_calc})^2} + \sqrt{(\mathrm{TE}_{9\_meas} - \mathrm{TE}_{9\_calc})^2}}{3}, \quad (5)$$

$$OF_5 = \frac{\sqrt{(\mathrm{TE}_{10\_meas} - \mathrm{TE}_{10\_calc})^2} + \sqrt{(\mathrm{TE}_{11\_meas} - \mathrm{TE}_{11\_calc})^2} + \sqrt{(\mathrm{TE}_{12\_meas} - \mathrm{TE}_{12\_calc})^2} + \sqrt{(\mathrm{TE}_{13\_meas} - \mathrm{TE}_{13\_calc})^2}}{4}, \quad (6)$$

$$OF_6 = \sqrt{(\mathrm{TE}_{14\_meas} - \mathrm{TE}_{14\_calc})^2}, \quad (7)$$

where TE_{j_meas} and TE_{j_calc}; $j \in [1,\ldots,14]$ is measured and calculated value of temperature, respectively. Weights 1, 1/2, 1/3 and 1/4 are based on the number of thermoelements within the expression. Objective function (1) calculates the value of the parameter values applied in the fuse model. Table IV shows the minimum and maximum values of the calculated variables, that are based on [5]–[7].

TABLE IV. MINIMUM AND MAXIMUM VALUES OF THE CALCULATED PARAMETERS

Parameter	Minimum value	Maximum values
p_1 [W/m^2·K]	1	15
p_2 [W/m^2·K]	1	15

A. Results

The suggested method for calculating a fuse's convection factor is confirmed comparing the measured and calculated results. The optimization calculated parameters values are shown in Table V, and are used in the following temperature calculations.

TABLE V. CALCULATED PARAMETER VALUES AFTER THE OPTIMIZATION PROCEDURE

Parameter	Value after optimization	Value before optimization
p_1 [W/m^2·K]	12.1	8
p_2 [W/m^2·K]	11.9	7.5

The measured and calculated temperature using the catalogue and optimization calculated parameters are compared in Table VI. Results in Table VI present very good agreement between measured and calculated results using parameter values after optimization.

TABLE VI. MEASURED (T_{MEAS}) AND CALCULATED (T_{CALC}) TEMPERATURES OF THE FUSE USING THE CALCULATED PARAMETERS AFTER OPTIMIZATION

Thermoelement	TE_1	TE_2	TE_3	TE_4	TE_5	TE_6	TE_7	TE_8	TE_9	TE_{10}	TE_{11}	TE_{12}	TE_{13}	TE_{14}
T_{meas} [°C]	81.3	92.5	81.9	94.2	86.5	83.7	76.5	83.7	85.9	125.3	134.1	134.4	131.2	88.9
T_{calc} [°C]	81.7	82.8	81.8	82.9	83.4	83.5	84.9	79.6	82.7	121.8	133.4	133.3	130.8	82.8

V. CONCLUSION

This paper applies the DE to calculate the convection factor values of LV melting fuse in order to evaluate the fuse's temperature. This method is based on the 3D simulation model of the fuse and temperature measurements. The temperature measurements were carried out in the laboratory using thermosensors. The convection factor of fuse contacts and ceramic body were determined by using the DE optimization algorithm. After analyzing the obtained results, there is satisfying matching between the calculated and measured temperature. This makes the DE algorithm appropriate for calculation of convection factor in applications as described in this article. The calculated parameter values are of vital importance for the designing process of a fuse and can be used for similar apparatus that uses the identical materials (fuse contacts and ceramic body).

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