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INVESTIGATION AND NUMERICAL SIMULATION OF A HIGH-CURRENT AC CIRCUIT BREAKER

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Abstract. The article is devoted to the study of the high-current AC circuit breaker. The results of the study are presented for various configurations of the arc divider. The study includes methods of spectral diagnostics and high-speed camera shooting synchronized with the electrical characteristics of the circuit breaker (current, voltage) in time. The obtained results allow to determine the composition of the plasma and dynamics of changes in the composition of the discharge in time. Calculation of the plasma composition and properties is made according to the obtained data, which makes it possible to take into account the products of circuit breaker materials ablation in numerical simulation. Non-stationary two-dimensional mathematical model with a moving mesh is developed. The obtained results allow to correct and verify the developed mathematical model of the circuit breaker operation. The evaluation of the arc divider influence is presented in the article.

Keywords: circuit breaker, plasma, simulation, mathematical model.

1. Introduction

The most famous and most used protection device is circuit breaker. And there is no universal method for design of a circuit breaker at the moment, but taking into account the development of computing technology, the possibility of multiphysical simulation [1] and optimization of the circuit breaker design appears. Different non-stationary mathematical models were created for analysis the circuit breaker operations previously, but all of these models did not take into account moving process of movement contact and ablation processes [1–3]. The main problem is the creation of a moving mesh, which leads to high demands on computing equipment.

There is little software which allows simulating using moving mesh and COMSOL Multiphysics is one of them. Several mesh smoothing methods are implemented in this software:

- ☐ Laplace smoothing (PDE method)
- ☐ Winslow smoothing
- ☐ Hyperelastic smoothing
- ☐ Yeoh smoothing

Laplace smoothing [4–6] introduces deformed mesh positions x and y as degrees of freedom in the model and it can be described in the static case by the following equation:

$$\frac{\partial^2 x}{\partial X^2} + \frac{\partial^2 x}{\partial Y^2} = 0, \qquad (1)$$

where x is the spatial coordinate of the spatial frame,

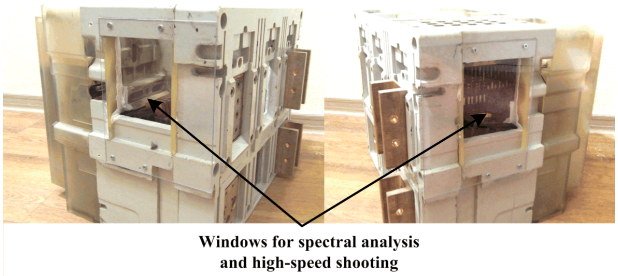

Figure 1. The circuit breaker prototype.

and X and Y are the reference coordinates of the material frame.

And in the transient case (which is most interesting for non-stationary mathematical model of a circuit breaker operation), it can be described by the following equation:

$$\frac{\partial^2}{\partial X^2}\frac{\partial x}{\partial t} + \frac{\partial^2}{\partial Y^2}\frac{\partial x}{\partial t} = 0. \qquad (2)$$

Similar equations hold for the y coordinate. The speed of the movement contact is determined from the results of high-speed shooting (described below).

The circuit breaker prototype was produced for experimental studies with special windows (see Figure 1) for high-speed shooting and spectral analysis.

Different types of arc dividers (which were investigated) are presented in Figure 2.

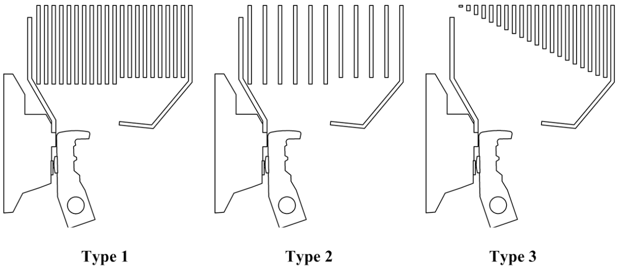

Figure 2. Investigated types of arc dividers.

2. Description of mathematical model

As mentioned earlier, the simulation of the circuit breaker operation is multiphysical task, which includes the following physical tasks: Maxwell's system of equations, momentum equation (Navier-Stokes equation) with continuity equation, heat balance equation (fluid and solid) and Laplace smoothing for moving mesh.

The circuit-breaker geometry is implemented with the ability to supplement the physical interface (for example, to solve the arc suppression problem, heating and erosion of the contact system) and the possibility of varying the position of individual components in the COMSOL Multiphysics software.

In addition, the simulation requires the dependences of the plasma thermophysical properties on temperature. The procedure for calculating the properties as a function of the plasma composition is presented in [7, 8].

The non-stationary mathematical model of the circuit-breaker operation is based on the following assumptions:

- ☐ Plasma is in a local thermodynamic equilibrium (LTE)
- ☐ Thermodynamic and transport properties depend on temperature
- ☐ Plasma is considered as laminar single-phase flow
- ☐ Near-electrode processes are not taken into account
- ☐ Plasma is optically thin

Basic equations describing non-stationary processes in DC circuit breaker:

☐ Maxwell's system of equations:

$$\begin{cases} \nabla \times \vec{H} = \vec{J} \\ \vec{B} = \nabla \times \vec{A} \\ \vec{J} = \sigma \vec{E} + \vec{J_e} \\ \vec{E} = -\frac{\partial \vec{A}}{\partial t} \end{cases} \tag{3}$$

☐ Momentum equation (Navier-Stokes equation):

$$\rho \frac{\partial \vec{v}}{\partial t} + \rho(\vec{v}\nabla)\vec{v} = \vec{F} + \nabla[-p\mathrm{I} + \mu(\nabla\vec{v} + (\nabla\vec{v})^{\mathrm{T}})] \tag{4}$$

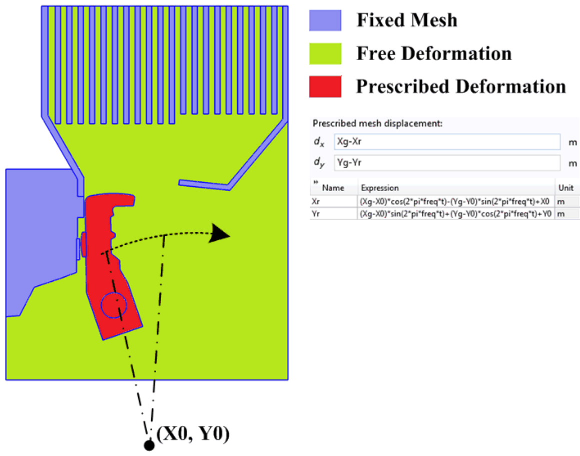

Figure 3. Boundary conditions for "Moving Mesh" interface.

☐ Continuity equation:

$$\rho \frac{\partial \vec{v}}{\partial t} + \nabla(\rho\vec{v}) = 0 \tag{5}$$

☐ Heat balance equation:

$$\rho C_p \frac{\partial T}{\partial t} + \rho C_p \vec{v} \nabla T - \lambda \nabla^2 T = Q_{\mathrm{s}} - Q_{\mathrm{rad}} \tag{6}$$

Computational domain and boundary conditions for "Moving Mesh" interface are presented in Figure 3.

The rotation is prescribed with respect to the undeformed coordinates X_g and Y_g using the following equations:

$$X_r = (X_g - X_0)\cos(2\pi f t) - (Y_g - Y_0)\sin(2\pi f t) + X_0, \tag{7}$$

$$Y_r = (X_g - X_0)\sin(2\pi f t) - (Y_g - Y_0)\cos(2\pi f t) + Y_0, \tag{8}$$

where X_0, Y_0 are origin coordinates; t is simulation time; f is determined by the velocity of the contact movement (from high-speed shooting).

The images of high-speed shooting research are shown in Figure 4. The total "switch off" time for contacts is about 20 ms and frequency f is about 2 Hz (from high-speed images).

Another important aspect is the setting of material properties. The properties for most materials (see Figure 5) are well known, with the exception of the main contacts material.

The method of air properties calculating taking into account the ablation of contact materials according to the results of spectral analysis is described in [7–9].

Main contacts material is KMK-A40 in accordance with the Russian Technical Specification (TS 16-685.020 - 85). Composition of KMK-A40:

- ☐ Silver - 95%
- ☐ Carbon - 5%

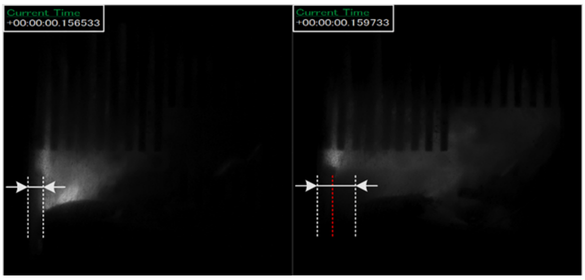

Figure 4. The high-speed images for the movement contact velocity identification.

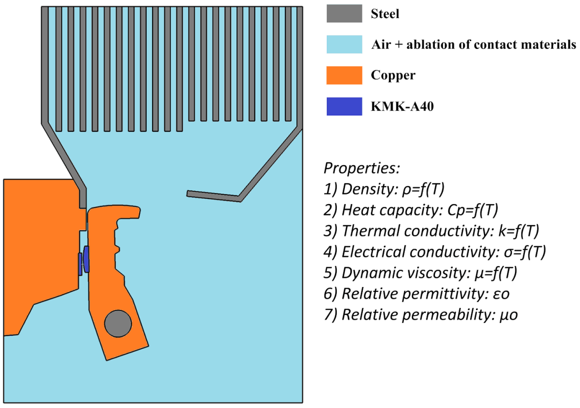

Figure 5. Materials of computational domain.

The calculated properties of the KMK-A40 material used in the simulation are shown in Figure 6.

The dependence of the current on time (obtained from experimental studies, see Figure 7) was used as data source for electrical task.

3. Simulation results

Numerical simulation was performed in Comsol Multiphysics software using the following physical interfaces:

☐ Laminar Flow (spf)

☐ Heat Transfer in Fluids (ht)

☐ Electric Currents (ec)

☐ Magnetic Fields (mf)

☐ Moving Mesh

☐ Multiphysics

- Nonisothermal Flow (nitf)
- Electromagnetic Heating (emh)
- Lorentz Force (lf)

Segregated solver with temperature lower limit was chosen as an algorithm for simulation of the circuit-breaker operation.

One of the main results of simulation is the temperature distribution inside the circuit breaker chamber. The temperature distributions at different times are shown in Figure 7.

The simulation results are confirmed by the results of the experimental study. New arc attachment point

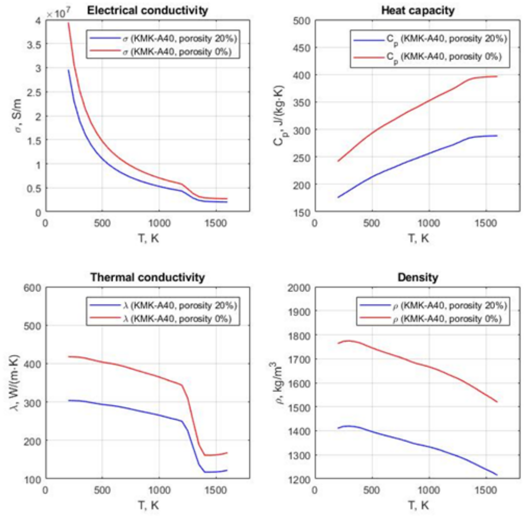

Figure 6. KMK-A40 properties depending on temperature.

formation is observed during the simulation a lot of times, which corresponds to the arc voltage fluctuation (from experimental study).

4. Results of experimental study

Experimental study included synchronized spectral analysis data, high-speed camera shooting and electrical parameters data (current and voltage waveforms). Analysis of the breaking capacity was performed on the basis of experimental study with similar electrical parameters of the power grid and the same moment of "switch off" operation. The results of experimental studies for various types of arc dividers (see Figure 2) are presented in Figure 8.

5. Conclusion

Non-stationary two-dimensional mathematical model with a moving mesh is developed. Laplace smoothing method was used for mesh generation. The speed of the movement contact is determined from the results of high-speed shooting (see Figure 4). KMK-A40 properties were calculated and presented (see Figure 6).

The simulation results are consistent with the experimental data. Experimental study of breaking capacity were performed for various modes and types of arc divider. The results for one of the modes are shown in Figure 8. The best result was observed when using the arc divider type 2.

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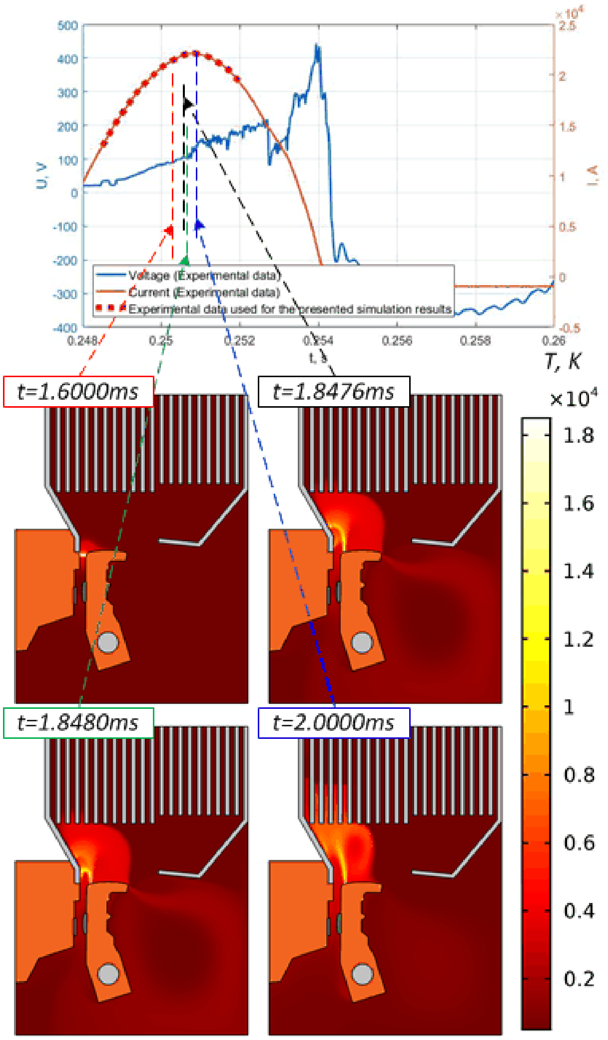

Figure 7. Results of experimental study and numerical simulation.

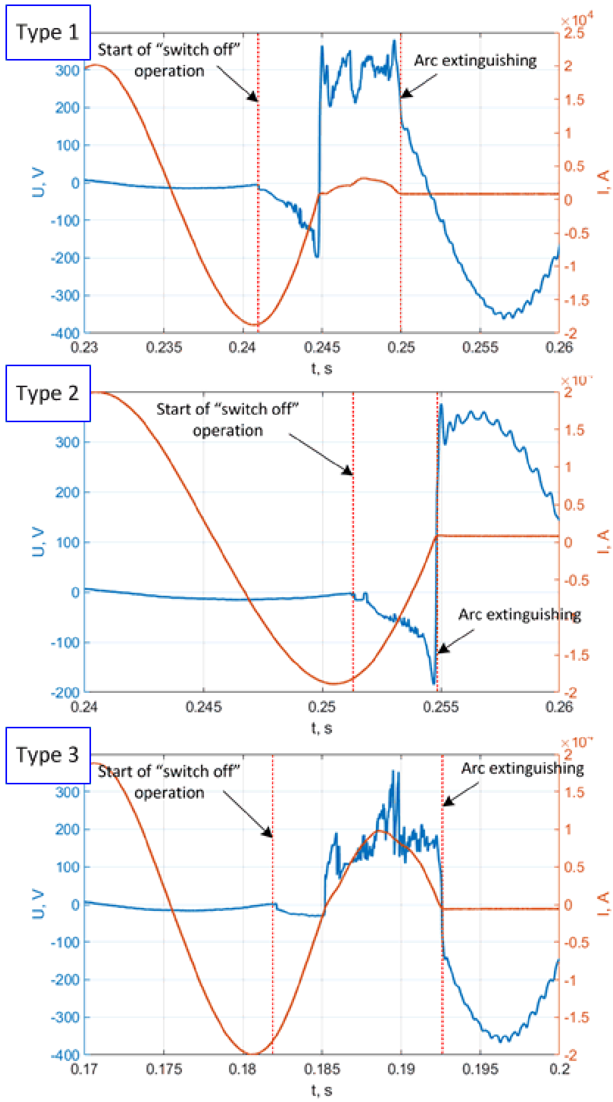

Figure 8. Voltage and current waveforms for different types of the circuit breaker arc divider.

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