Numerical simulation of heat transfer processes of the circuit breaker contact system

Iu Murashov*, V Frolov and A Kvashnin
Peter the Great St.Petersburg Polytechnic University, St.Petersburg, Polytechnicheskaya 29, 195251, Russia

* E-mail: iuriimurashov@gmail.com

Abstract. The article is devoted to the study of heat transfer processes of the high-current AC circuit breaker contact system. The creation of a mathematical model is based on the application of well-known physical laws such as the Joule-Lenz and Fourier laws, which describe physical processes in the form of partial differential equations. Cooper-Mikic-Yovanovich correlation is used for evaluation of thermal and electrical contact conductance. The developed mathematical model is verified by the results of experimental studies. The calculation of the composite material properties for numerical simulation of heat transfer processes is presented. The calculation is presented for the actual design and materials of the circuit breaker.

1. Introduction

The most famous and most used protection device is circuit breaker [1-5]. And there is no universal method for calculating the design of a circuit breaker at the moment, but taking into account the development of computing technology, the possibility of multiphysical simulation [6, 7] and optimization of the circuit breaker design appears. There are a large number of models describing the thermal and electrical conductivity of a contact. All of these models are empirical and require additional verification. The Cooper-Mikic-Yovanovich correlation was chosen to calculate the thermal and electrical conductivity of the circuit breaker contact system. The cooper-Mikic-Yovanovich correlation (plastic deformation model) is described by the following equation [8-10]:

$$h_c = 1.25 \sigma_{contact} \frac{m_{asp}}{\sigma_{asp}} \left( \frac{p}{H_c} \right)^{0.95}, \quad (1)$$

$$\sigma_{contact} = \frac{2\sigma_u \sigma_d}{\sigma_u + \sigma_d}, \quad (2)$$

where $m_{asp}$ is surface roughness, asperities average slope; $\sigma_{asp}$ is surface roughness, asperities average height; $p$ is contact pressure; $H_c$ is microhardness; $\sigma_u, \sigma_d$ are electrical conductivities of contact materials.

$m_{asp}$ and $\sigma_{asp}$ can be determined using Russian GOST standards 3884-77.

Composite material KMK-A40 is used as a contact pad. This composite material is made in accordance with the specifications TS 16-685.020-85. According to the specification, the Brinell hardness is about 150 kPa. Microhardness is related to Brinell hardness by the following equations:
\[ \frac{c_1}{H_0} = 4.0 - 5.77 \frac{H_B}{H_0} + 4.0 \cdot \left( \frac{H_B}{H_0} \right)^2 - 0.61 \cdot \left( \frac{H_B}{H_0} \right)^3 \]  

\[ c_2 = -0.370 + 0.442 \cdot \frac{H_B}{c_1} \]  

\[ \frac{p}{H_c} = \left( \frac{p}{\frac{1.62 \left( \frac{\sigma_{up}}{m_{up} \sigma_0} \right)}{c_2} c_1} \right)^{1/0.07c_2} \]  

where \( H_B \) is Brinell hardness; \( H_B = 3.178 \) GPa.

Contact pressure was indicated from the mechanical task (see Figure 1).

**Figure 1.** Construction of circuit breaker contact system and contact pressure.

### 2. Material properties used

Another important aspect is the setting of material properties. The properties for most materials (see Figure. 1) are well known, with the exception of the main contacts material. 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%
Porosity – 20%

The composite material (KMK-A40) density can be evaluating according to the expression:

$$\rho_{KMK-A40}(T) = \frac{(1-P)\rho_{Ag}(T)\rho_{C}(T)}{\varphi_{Ag}\rho_{Ag}(T) + \varphi_{C}\rho_{C}(T)}, \quad (6)$$

where $P$ is porosity; $\rho_{Ag}$, $\rho_{C}$ are silver and carbon densities; $\varphi_{Ag}$, $\varphi_{C}$ are silver and carbon concentrations.

Thermal conductivity of a non-porous composite material (solid phase) consisting of two components can be evaluating according to the expression [11, 12]:

$$k(T) = \varphi_{Ag}k_{Ag}(T) + \varphi_{C}k_{C}(T) \quad (7)$$

Thermal conductivity with regard to porosity:

$$k_{KMK-A40}(T) = k(T)\left(1 - 3\frac{P}{2 + P}\right) \quad (8)$$

Heat capacity of a non-porous composite material can be evaluating according to the expression:

$$C_p(T) = \varphi_{Ag}C_{p,Ag}(T) + \varphi_{C}C_{p,C}(T) \quad (9)$$

Heat capacity with regard to porosity:

$$C_{p,KMK-A40}(T) = C_p(T)\left(1 - 3\frac{P}{2 + P}\right) \quad (10)$$

Electrical conductivity of KMK-A40 can be evaluating according to the expressions:

$$\rho_{el}(T) = \frac{\rho_{el,Ag}(T)\rho_{el,C}(T)}{\varphi_{Ag}\rho_{el,Ag}(T) + \varphi_{C}\rho_{el,C}(T)} \quad (11)$$

$$\rho_{el,m}(T) = \frac{1}{\rho_{el}(T) + \sqrt{\frac{16}{\rho_{el}(T)} + \frac{1}{\rho_{el,Ag}(T)\rho_{el,C}(T)}}} \quad (12)$$

$$\rho_{KMK-A40}(T) = \rho_{el,m}(T)\left(1 - \frac{P}{1 - 2P}\right) \quad (13)$$

$$\sigma_{KMK-A40}(T) = \frac{1}{\rho_{KMK-A40}(T)} \quad (14)$$

The obtained temperature dependences are shown in Figure 2.
Figure 2. KMK-A40 properties depending on temperature.

3. Mathematical model
Simulation of heat transfer processes of the circuit breaker contact system is multiphysical task. «Electric Currents» and «Heat Transfer in Solids» physical interfaces of Comsol Multiphysics are used for solving this task.

Basic equations of the “Electric Currents” physical interface:

\[ \begin{align*}
\nabla J &= Q, \\
\vec{j} &= \sigma \vec{E} + \vec{J}_e, \\
E &= -\nabla V
\end{align*} \]  

The “Terminal” condition is set as one of the boundary conditions, where the current value is set to 1 kA, which is selected based on the availability of experimental data, which allows to verify the developed mathematical model. Creating a closed circuit is implemented by setting the boundary condition "Ground". The boundary condition “Ground” corresponds to the zero value of the scalar potential \( V=0 \).

Simulation of temperature distribution in the contact system was carried out using the “Heat Transfer in Solids” physical interface.

Basic equation of the physical interface "Heat Transfer in Solids (Fluids)"

\[ \rho c_p \frac{\partial T}{\partial t} + \rho C_p V + \nabla \cdot (-\lambda \nabla T) = Q \]  

The volume of airspace is excluded from the calculation in order to reduce the requirements for a computing system, and heat transfer from the contact surface is set in the form of the “Heat Flux” boundary condition — convective heat transfer. Equation (16) takes the following form in this case:
\[
\rho C_p \frac{\partial T}{\partial t} + \nabla \cdot (-\lambda \nabla T) = Q
\]

(17)

The boundary condition "Heat Flux" has the following form:

\[q_a = h(T_{\text{ext}} - T)\]

(18)

The variable \( h \) is the heat transfer coefficient in equation (18), the numerical value of the coefficient depends on the properties and parameters of the convective flow [13-15]. The temperature value \( T_{\text{ext}} \) corresponds to the temperature value of the convective flows, the allowable temperature rises of the electrical apparatus parts are given in GOST 403-73.

There was identified the heat transfer processes from the individual parts of the apparatus is difficult due to the use of plastic material with thermal insulation properties. Therefore, the boundary condition "Heat Flux" is set on the surface of structural elements having sufficient space to implement the mechanism of convective heat transfer. The boundary conditions “Thermal Insulation” are specified at the remaining boundaries of the computational domain.

The communication between "Electric Currents" and "Heat Transfer in Solids" is implemented using "Multiphysics".

“Time Dependent” and “Stationary” were used as solvers. "Time Dependent" is a solver for time dependent variables, this allows us to estimate the dynamics of the simulated processes. “Stationary” is a solver for variables that do not change over simulation time or are in steady-state. This solution allows us to evaluate the temperature values for the steady-state (applied to the heating task).

4. Simulation results and verification of mathematical model

The simulation results of heat transfer processes of the circuit breaker contact system corresponding to the experimental study are presented in Figure 3. These results were obtained for a fixed ambient temperature of 20 °C.

Verification of the mathematical model is carried out in comparison with the experimental data performed with similar to the simulated modes.

The time dependences of the maximum temperature on the surface (simulation results), the maximum temperature of the circuit breaker contact system in the steady-state, and experimental data are presented in Figure 3.
Figure 3. Simulation results and experimental data.

Absolute error does not exceed 4 °C, and does not exceed 1 °C in the steady-state, taking into account the simplification of the mathematical model and the accepted assumptions, the simulation results are in sufficient agreement with the results of the experimental study. The obtained results allow us to verify the mathematical model of the circuit breaker contact system.

5. Conclusion
Non-stationary three-dimensional mathematical model of heat transfer processes of the high-current AC circuit breaker contact system is developed. The mathematical model includes Cooper-Mikic-Yovanovich correlation. The calculation of the composite material KMK-A40 properties is presented. Experimental studies were performed to verify the developed mathematical model. The numerical simulation results are confirmed by experimental data (absolute error does not exceed 4 °C, and does not exceed 1 °C in the steady-state).

The proposed method can significantly reduce the number of experimental studies in the design of insulators, which will lead to a decrease in financial costs.

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