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ANALYSIS OF ELECTROMAGNETIC PROCESSES INSIDE THE ARC INTERRUPTING SYSTEM OF A HIGH-CURRENT CIRCUIT BREAKER

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Abstract. Description of electromagnetic processes inside an arc interrupting system of high-current circuit breaker is presented in article. Non-stationary mathematical model of the circuit-breaker operation (short-circuit currents mode) is developed. The main regularities of the displacement of the electric arc inside an arc chute are established. The influence of the movable contact position on the conditions for the displacement of the electric arc is presented. Also, the influence of the arc chute material on the motion and interrupting of an electric arc (alternating and direct currents) is established.

Keywords: circuit breaker, mathematical model, electrical switch, short circuit.

1. Introduction

The main device for protecting low-voltage distribution power grids from overload and short-circuit currents is an circuit breaker. Circuit breakers are received the widest application in alternating current circuits. There are several theories of electric arc extinction and current interruptions, which are based on the theories of Slepian and Cassie [1, 2].

The operation of the circuit-breakers is determined and by other factors besides the the electric arc extinction, for example, by the thermal state of the contacts during a long and short-term discontinuity under current load.

The subsequent rejection of the movable contact (accompanied by the formation and arc extinction) depends on the organization of the magnetic damping of the arc.

The consequences of a current transfer high speed ($\approx$ 400–500 A/µs) from main contacts to arc-extinguishing contacts can lead to failure of the device due to strong erosion of electrodes and even their welding, violating its functional capacity for current switching. The existing drive devices speed and the pulling force of the arc-extinguishing contacts allows the commutation process to be completed in the same half-cycle when the current passes through zero at the beginning of the arc contacts dilution in the growing section of the short-circuit current.

Maximum current value can reach half the amplitude of the expected short-circuit current during the current rises in the transient mode, as follows from the above. This makes it possible to estimate and take into account in the analysis of the main-contact system heating with the current transfer speed 400–500 A/µs. It shows necessary to ensure the arc-extinguishing contacts pressing increase (not leading to their welding). It means the rate of pressure increase should outrun the rate of current rise, which causes the contact pad heating up to the melting temperature.

Ensuring the current transition from the main contacts to arc-extinguishing contacts without electric arc is the main task of the rotary mechanism for the dilution of movable contacts. There is a weakening of the main contacts (silver-based lining) pressing and increasing the arc-extinguishing contacts (copper contacts) pressing during the current flows from the main to the arc-extinguishing contacts.

2. Theoretical investigations

The parameters of the arc-extinguishing contacts transient resistance (during their compression depending on the closing speed, the material parameters and the contact surface) can be determined according to the energy conservation equation [3]:

$$m\left(\frac{\mathrm{d}h}{\mathrm{d}t}\right)^2 + kh^{\frac{5}{2}} = \frac{mv^2}{2} + \frac{1}{2}Ph \qquad (1)$$

where $k = \frac{8}{15}\sqrt{r_c\Theta}$ - coefficient taking into account the shape and elastic properties of the contacts; r_c - equivalent radius of the contact surface curvature; Θ - coefficient taking into account the contact material, Poisson's ratio and elastic modulus of moving and stationary contacts [3]; P - force applied to contacts; h - rapprochement of contact bodies; m - mass of movable contact; v - speed of the contacts approach at the moment of their contact. The maximum approach of contacts corresponds to the moment when $\frac{\mathrm{d}h}{\mathrm{d}t} = 0$. In this case, equation (1) takes the form:

$$kh^{\frac{5}{2}} = \frac{mv^2}{2} + \frac{1}{2}Ph \qquad (2)$$

It is possible to determine the maximum approach of contacts h when they are compressed by solving this equation. At the same time, the compression time of the electrodes: $t = \frac{h}{v}$.
The current transfer from the main contacts to arc-extinguishing contacts without electric will be realized in the absence of melting of a large mass of electrodes in the transient mode of the current, as well as a complete transition of the current to the arc-extinguishing contacts until the moment of throwing the movable contact by the rotary mechanism.Otherwise, if the current from the main contacts does not have time to go to the arc-extinguishing contacts, the arc will ignite on the main contacts. This will lead to an increase in erosion of the main contacts.
The change in the contact resistance of the arc-extinguishing contacts during compression by [3] will be:

$$R = \frac{\rho_0\left(1 + \frac{2}{3}\alpha T_{\mathrm{mel}}\right)}{2\sqrt{\frac{h}{2A_s}}f_c} \qquad (3)$$

where ρ_0 - specific electrical resistance of electrode material; α - temperature coefficient ($0.0042\,\mathrm{K}^{-1}$); T_{mel} - melting temperature of contact material; $A_s = \frac{1}{2R_s}$ - coefficient taking into account the curvature of the contact surface (sphere-plane); f_c - coefficient taking into account the ratio of the contact area at the end and the beginning of compression (≈2.25).

2.1. Calculation of the electrodynamic forces

The following forces act on the arc at the extinction:

☐ The electrodynamic force $F_\perp$ due to the location of the arc (conductor with current) between two contacts

☐ The electrodynamic force F_μ due to the location of the arc near the ferromagnetic plates

☐ The electrodynamic force $F_\sim$ due to the variable component of the short-circuit current

Calculations of the electrodynamic forces are performed for the distance a between contacts. The angle 0° corresponds to the fully open state of the contacts. The angle $-6°$ corresponds to near a state close.
The results of the electrodynamic force $F_\sim$ estimated calculation acting on the electric arc in the circuit-breaker are presented in Table 1 for four variants of contact opening time (2, 3, 4, 5 ms). The electrodynamic forces $F_\perp$ and F_μ don't depend on time. The results of the electrodynamic forces estimated calculation are presented in Table 2. The electrodynamic forces $F_\perp$ and F_μ can be compared with the electrodynamic force $F_\sim$ (see Table 1).

t[ms]	α	a[mm]	$F_\sim$[N]
2	$-6°$	21	446
	$-3°$	28	576
	$0°$	36	693
3	$-6°$	21	948
	$-3°$	28	1167
	$0°$	36	1314
4	$-6°$	21	1551
	$-3°$	28	1782
	$0°$	36	1815
5	$-6°$	21	2175
	$-3°$	28	2274
	$0°$	36	2007

Table 1. The electrodynamic force $F_\sim$.

α	a[mm]	$F_\perp$[N]	F_μ[N]
$-6°$	21	2084	256
$-3°$	28	2499	342
$0°$	36	2828	433

Table 2. The electrodynamic forces.

2.2. Mathematical model (heat transfer task)

A steady-state temperature rise is adopted as an excess of temperature during the device operation in a continuous mode; the maximum temperature rise is adopted during operating in a short-time mode at the end of the operating periods. According to Russian standards, the test should be continued until a steady temperature is reached, but not more than 8 hours.In the case of applying numerical methods, it is possible to calculate the steady-state operating mode when the rated current flows through the contact system. The geometry of the existing switching contacts of the main circuit was used in the development of a mathematical model (see figure 1).

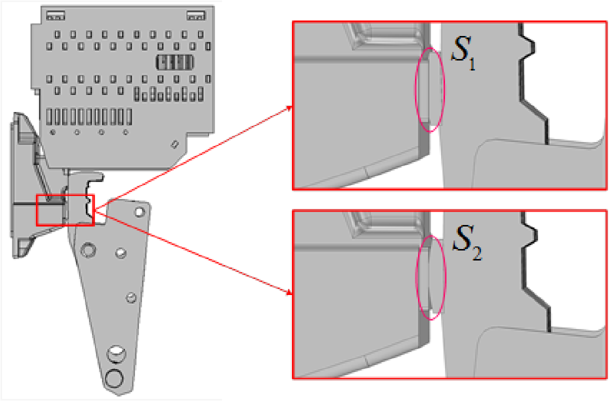

Figure 1. Geometry of contacts.

The area of the contact surface $S_1 > S_2$ (see figure 1), which allows us to analyze the effect of the contact surface area on the contact system heating (it is possible to establish the force of pressing the

contacts in solving a mechanical task).
Basic equations of mathematical model:

$$\rho C_p \frac{\partial T}{\partial t} + \nabla(-\lambda \nabla T) = Q \tag{4}$$

$$\begin{cases} \vec{J} = Q_j \\ \vec{J} = (\sigma + \epsilon_0 \epsilon \frac{\partial}{\partial t})\vec{E} + J_{\text{ex}} \\ \vec{E} = -\nabla V \end{cases} \tag{5}$$

Heat removal from the contact surface (convective component):

$$q_0 = h(T_{\text{ext}} - T) \tag{6}$$

where h - heat transfer coefficient [4], the numerical value of the coefficient depends on the properties and parameters of the convective flow. The simulation results in the case of a contact surface $\approx 340\,\text{mm}^2$ are shown in figure 2).

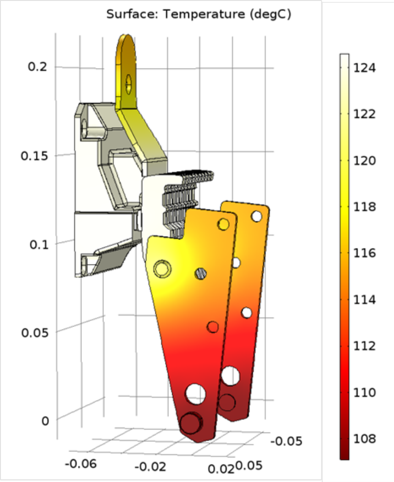

Figure 2. Temperature distribution.

The maximum value of the temperature is 124.6 °C, according to the results of experimental studies, the maximum value is 127 °C.

2.3. Mathematical model (electrostatic task)

From the experimental results it was dedicated that the arc interrupting system is not fully engaged during arc extinguished. It is necessary to provide a high electric field strength in the contact area of the interrupting system to ensure the formation of attachment on the contact of the arc interrupting system and intensive retraction of the arc into the interrupting grid [5],which value will exceed the value of electric field strength near the movable contact (see figure 3). A preliminary analysis of the electric field strength is made on the basis of simulation results of a two-dimensional electrostatic mathematical model of a circuit breaker. The model is based on the existing geometry of the circuit breaker.
The mathematical model is based on the Gauss law for an electric field:

$$\begin{cases} \vec{E} = -\nabla V \\ \nabla(\epsilon_0 \epsilon_r \vec{E}) = \rho_V \end{cases} \tag{7}$$

The results of numerical simulation are shown in figure 4.

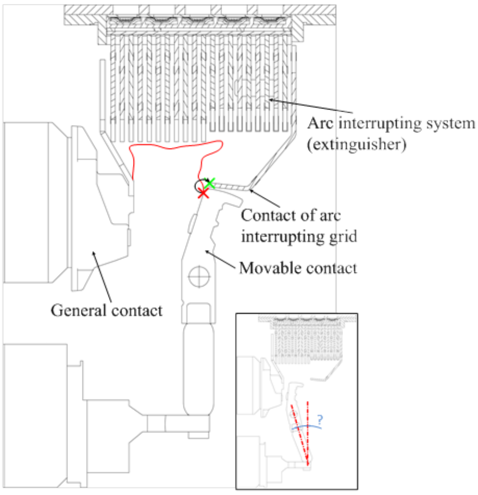

Figure 3. Geometry of contact system.

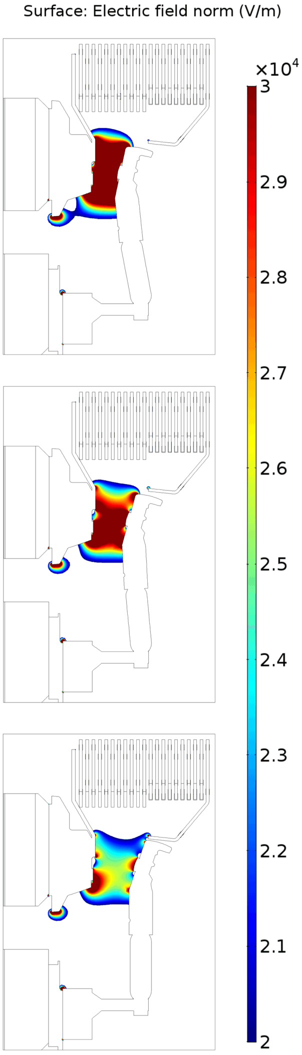

Figure 4. Electrical field strength distribution.

3. Conclusions

The change in the scalar potential inside the ferromagnetic grid is greater in the case the contact of the arc interrupting grid has a zero electric potential. This means that conditions are created for stretching the arc over the entire length of the ferromagnetic grid.

The electric field strength has high values in the contact area of the arc grid with the greatest contact dilatation, which causes strong emission of electrons from the cathode surface and guarantees the attachment at the contact of the arc grid, which leads to an intensive retraction of the arc into the arc interrupter.

The main forces acting on the arc are $F_{\perp}$ (prevails in the interval of contact opening time 2–3 ms) and $F_{\sim}$ (prevails in the interval of contact opening time 4–5 ms).

The maximum temperature does not exceed 125 °C with a long current of 4 kA, which corresponds to the national standards for contact materials used (it follows from the simulation results).

Optimization of the arc interrupting system design based on the simulation results of the electrostatic task.

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