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LOW-VOLTAGE CIRCUIT-BREAKER BEHAVIOR UNDER OVERLOAD CONDITIONS

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Abstract. This article deals with temperature-rise of current path of modern low-voltage circuit-breaker with rotary contact system at overloads and subsequent experimental verification of selected model. The first part describes optimal setting of input conditions of simulation and mainly transient phenomena at contacts causing dynamic change of contact resistances due to change of total contact force, a new challenge to be solved in this contribution. The second part devotes laboratory measurement on prepared sample of the breaker for verification of transient simulation. These simulations are not only important for understanding of rotary system behavior under overloads, but forms an essential part of R & D process due to the speed-up of optimal current path design. In the end, both the financial costs and time effort could be decreased.

Keywords: low-voltage circuit-breaker, overload, Holm force, thermal losses, SolidWorks Flow Simulation.

1. Introduction

To speed up the development of a new switching device and reduce necessary costs, various kinds of numerical models describing selected phenomena have been practically used for more than twenty years.

One of the key parts of the whole device is correctly and optimally designed current path with respect to thermal load during steady-state conditions (under rated load) as well as transient conditions (under overload conditions - several multiples of rated current).

One of the significant heat sources in current path is contact area due to the higher electrical and thermal resistances. Contact resistance is a very difficult and complex phenomenon to be dealt with not only in numerical models [1–5]. This issue is emphasized in nowadays widely used rotary system of contacts, where two contact resistances occur.

First numerical models were the steady-state ones with very simple model of contact resistance and only some of heat transfer modes were considered - those which were essential for very beginning rough design of first prototypes. Gradually more and more complex models have been proposed with all heat transfer modes (conduction, convection and radiation). However, very precise numerical model including correct model of contact resistance is an issue till these days. This precise model is very important for reliable study of transient phenomena during overloads. Overload phenomena, such as possibility of exceeding temperatures of reliable connection between contact tips and their carriers, occur in addition to the rated loads. This article aims to contribute to this part of thermal simulation.

2. Numerical model and geometry

Mathematical model (governing equations) used for simulations below is based on well known system of partial differential equations known as Navier-Stokes equations describing basic conservation principles - conservation of mass, momentum and energy - e.g. [6, 7]. It is assumed that the reader is more or less familiar with these equations and they will not be repeated here.

To discretize these equations, several discretization methods can be used. Most frequently, Finite Element Method (FEM) or Finite Volume Method (FVM) are being used. The latter one is used in Software package SolidWorks with plug-in Flow Simulation. This software enables to solve all modes of heat transfer (conduction, convection and radiation), use special layer for electrical and thermal contact resistance, use either laminar (this case) or turbulent flow, comprise natural heat and include Joule heat losses which are used by means of an intensive quantity (generated losses per unit volume) and given by the following equation:

$$q = \gamma \cdot E^2. \tag{1}$$

In Eq. (1) q stands for density of Joule losses, γ conductivity of the material and E electric field intensity. Electric field intensity is obtained as a negative gradient from the scalar electric potential ϕ, which is obtained by discretization of the following equation:

$$div\, \gamma\, grad\, \phi = 0. \tag{2}$$

Problem of contact resistance model is separately explained in next paragraphs.

Figure 1 shows real final geometry of the breaker used for thermal simulations (steady-state and transient). The "control points" are depicted here as well. The whole geometry is enclosed in the corresponding housing and oriented by "line side" up from the natural convection point of view (thermal release - bottom).

Besides geometry and mathematic description of phenomena comprised in the model, one has to enter several input parameters, which is described in the next paragraph.

3. Input data for simulation

A lot of input parameters into simulation have to be known - comprising material data from various databases as well as specific data obtained from laboratory measurement for specific simulation.

Commonly required parameters such as density, specific heat, thermal and electrical conductivity and viscosity were considered as temperature dependent. Since radiation mode of heat transfer was also considered, it was necessary to input emissivity of surfaces of different construction materials.

3.1. Contacts and their properties

One of the most challenging thing in thermal simulations of electrical devices is to set proper properties of electrical contacts - electrical and thermal resistance. It is an issue even for new (i.e. non-eroded) contacts, not speaking of eroded contacts after power tests, where these properties are hardly to be estimated and vary one sample to the other. SolidWorks Flow Simulation allows treating this property via special layer of the contact surface that can be temperature dependent.

Simulated breaker has rotary contact system to be highly current limiting, which means there are two contacts attached to the contact lever in the middle - see Fig. 1. Contacts from both sides of the contact lever means that the connection to the contact lever is the most critical part at overloads.

There have been many formulas [3, 4] proposed to express electrical resistance between contacts. One of the most often used says that electrical resistance depends on materials of contact and resulting contact force:

$$R_s = k \cdot F_c^{-n}, \tag{3}$$

where R_s is contact resistance, k material dependent coefficient, F_c contact force and n exponent dependent on shape of contacts. E.g. for flat - cylinder shape, n could range from 0,5 to 0,7.

The contact force can be usually considered constant at steady-state conditions (temperature-rise for rated currents), i.e. the contact resistance remains unchanged throughout the simulation process.

The situation dramatically changes at overloads. The reason is repulsive (Holm) electrodynamic force due to current constriction at higher current levels - see Fig. 2.

The value of this force for single contact spot can be expressed by the following equation:

$$F_u = I^2 \ln \frac{D}{d} \cdot 10^{-7}, \tag{4}$$

where D is the diameter of contacts (for rectangular shape a x b can be expressed as $D = \sqrt{a \cdot b}$) and d diameter of a spot.

This force is negligible in comparison to spring force at rated current but rises significantly at higher currents meaning the total contact force reaches zero at pop-up level, when contacts start to separate. From the current limiting point of view, it is convenient to have pop-up level as low as possible. From the contact erosion point of view and possibility of contact welding, it is necessary to have pop-up level higher. Definitely it must be above maximum setting of short-circuit release otherwise the failure would be quite sure due to long reaction of thermal release. Considering these two contradictory requirements for pop-up level, the final result is that the contact force is significantly reduced at currents just below maximum setting of short-circuit release which are tripped by thermal release in the orders of seconds. It means the contact resistance is significantly higher for these currents, which in turn must be considered for proper thermal simulations at higher overloads. Figure 3 shows the contact resistance of line and load side as a function of contact force measured on one sample.

Fixed and movable contacts are made of materials based on powder metallurgy which are characterized as highly arc erosion resistant and weld resistant. On the other hand, they have to have sufficiently small contact resistance.

This change of contact resistance at higher overloads was taken into account for subsequent temperature simulations.

4. Temperature-rise simulation at overloads

The proposed and described numerical model was improved for different levels of overloads by taking into account change of both electrical and thermal contact resistance with repulsive (Holm) force.

These dependent electrical and thermal contact resistances were applied for selected model for different current levels at overloads (4x, 6x, 8x, 10x, 12x a 13x) I_r. As a critical temperature of contact tip - contact lever joint was considered 500 °C for specific technology of connection. For thermal release it means it has to be faster than time when this critical temperature is reached.

Figure 4 shows an example of temperature distribution for current of 10x I_r and time 5 s. Figure 5 shows temperature of various control points at the time, where contact joint (control point 5 or 6) reached critical temperature of 500 °C.

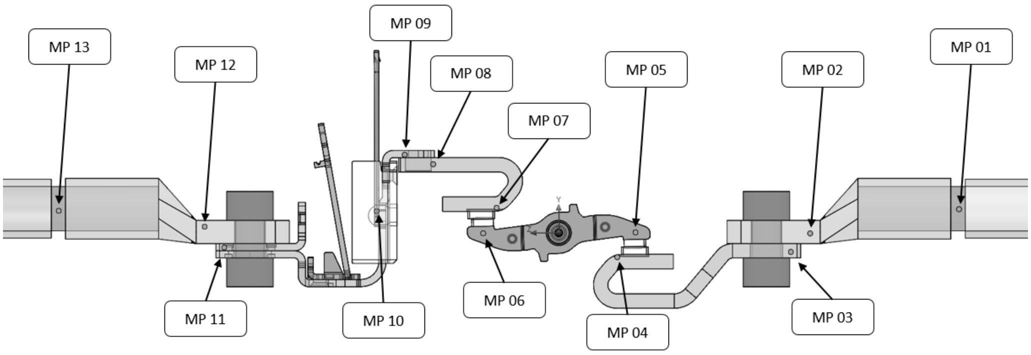

Figure 1. CAD model of the breaker current path used for simulations (both steady-state and transient) including control (measurement) points MP

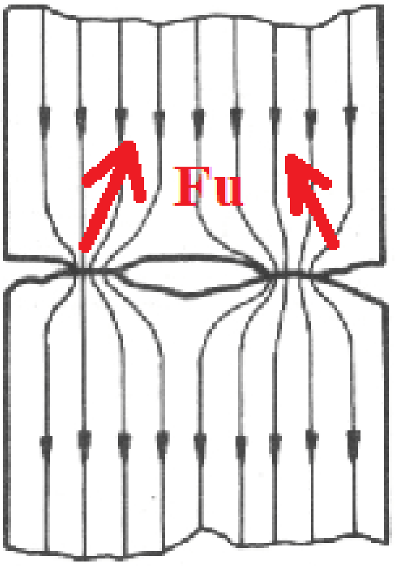

Figure 2. Repulsive electrodynamic force due to current constriction

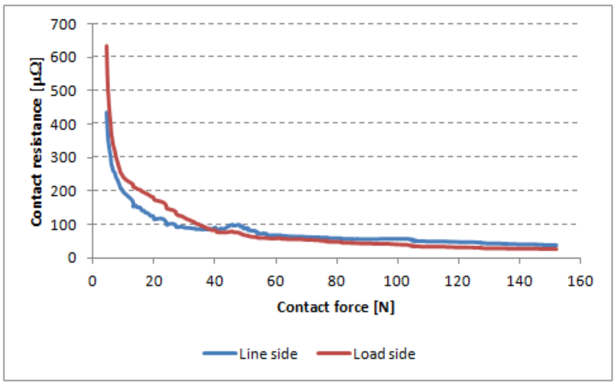

Figure 3. Contact resistance as a function of contact force for line and load side

5. Verification of numerical model at overload conditions

Based on the simulations, one sample was prepared for production and subsequently tested at overload conditions. At the same control points, the temperature was measured by thermocouples and saved into data logger. Only the middle pole was measured. The current flow was stopped after the contact joint points reached critical temperature. Table 1 and 2 show comparison between simulation and measurement for line and load side respectively. They show good agreement between simulation and reality in all current levels so it means the improved numerical model was verified and can be used for various designs comparison.

	Time to reach 500 °C			
x I_r	Meas. [s]	Sim. [s]	Δ [s]	Δ [%]
4	61	65	4	6.6
6	17.5	17.9	0.4	2.3
8	5.3	5.6	0.3	5.7
10	2.5	2.7	0.2	8.0
12	1.5	1.6	0.1	6.7
13	1.2	1.3	0.1	8.3

Table 1. Comparison of simulated results with measurement - line side

	Time to reach 500 °C			
x I_r	Meas. [s]	Sim. [s]	Δ [s]	Δ [%]
4	53	56	3	5.7
6	13.5	14.1	0.6	4.4
8	5.2	5.6	0.4	7.7
10	3.2	3.3	0.1	3.1
12	2.0	2.1	0.1	5.0
13	1.6	1.7	0.1	6.3

Table 2. Comparison of simulated results with measurement - load side

6. Conclusions

The verification of proposed numerical model of temperature-rise of the device current path showed that there is quite a good agreement between simulation and measurement when change of electrical and thermal contact resistances with increased current is taken into account. Maximum deviation was about

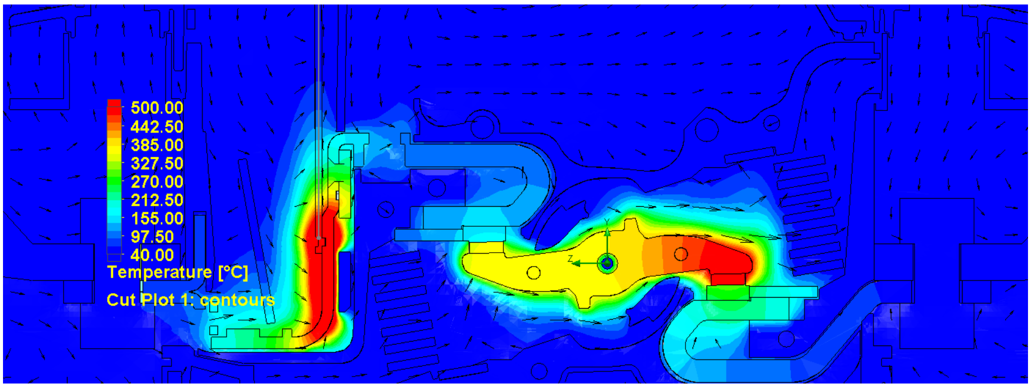

Figure 4. *Simulation of overload at 10x I_r and time 5 s*

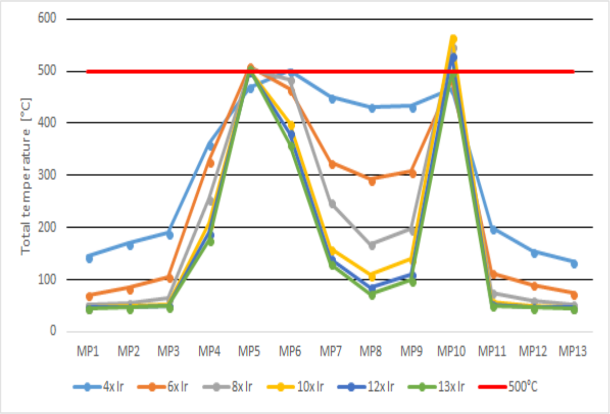

Figure 5. *Temperature of various control points MP for overload at time when MP5 or MP6 reached critical temperature 500 °C*

8 %, which is for this kind of simulation satisfying result making its practical usage possible. Without taking change of contact resistance into account, the error reached more than 30 % for some currents.

The simulated results also showed that for higher overloads critical temperature moves from contact lever to heater of the thermomagnetic release and has impact on proper bimetal release solution.

When the repulsive Holm force is calculated for each overload, the contact resistance can be recalculated to the resulting contact force very easily based on measurement data availability for various contact materials and their dimensions. Of course, this is valid for contacts in a new state. Temperature-rise simulations for eroded contacts still pose an issue, which will be focused in the future.

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