THERMAL STRESS OF CONTACTS AND CURRENT PATH OF LOW-VOLTAGE SWITCHGEARS

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SUMMARY

In the paper the results (temperature rise calculations) are presented for stationary arc root on both the contacts and the splitters (extinguishing chamber). By a breaking arc, that is an intensive thermal source, significant overheat of contacts is caused. This process makes for an intensive erosion of contact materials. Experiments oriented to erosion of materials and overheat of current path parts were made with contactors and miniature circuit breakers. Consequences owing to arc energy on the material erosion are presented. Steady state distribution of temperature along the current path of contactors was both calculated and measured. Method of equivalent thermal circuits and simulation in ANSYS were used to perform calculations.

Keywords: *electrical arc, thermal stress, contact, breaking arc energy, acumulated energy, erosion of contact material, thermal network*

1. INDRODUCTION

Electrical arc has a considerable significance in the technique of electrical devices.

The arc is implicitely connected with operation of electrical contact switches, unlike other electrical equipments. Most frequently an electrical arc occures in the switchgears. Origination of an arc is caused by contact mechanism itself. Electrical arc appears in the instant of opening the contact, i.e. an interuption of a circuit under current or in the case of closing a circuit with specific interuptions, i.e. when the circuit is closed by a vibrating contact.

An arc only exists very short time, expires when contact are settled – when the closed position is reached. This short time event may damage contact by increased contact erosion or even cause a welding of both contact sides together., causing a failure of correct function of a switchgear.

Repeated activity of an arc in the intermittent duty is typical for contactors. In most cases a contact operates a current up to its rated current value but electrical arc while breaking a short-circuit currents (10^2 – 10^3 A) applies an enormous stress to contact and extinguishing system. Arc time is short - several millisecond – but the energy applied to contact and extinguishing system is high (10^3 J). There is a temperature rise all along the current path as well as in whole device. Process of breaking an arc destructively affects both contacts and extinguishing parts. Erosion of materials occures due to the temperature, achieving the melting and evaporation values.

Dimensioning the current path is based on rated current value and character of protected or breaked circuit. Temperature of individual parts must not exceed allowed limit values. Direct calculation of current path temperature is hard if not impossible to perform because it is heat transfer dependand. In the last years modelling and simulation (CAMS) is used in research and development of new equipments. Computer aided modelling and simulation of temperature fields are used also for computing a current path of low-voltage contactors.

2. THERMAL STRESS OF CONTACTS DURING THE BREAKING PROCESS

The breaking arc is a short-time transient regime operating as an intensive thermal source and leads to resolute increase of temperature in the spot of the arc root. Theoretical investigation of this process provides a determination of temperature layout over the contact.

Temperature is a function of time and space coordinates. Solution of the problem has a form of thermal field, or a time-space distribution of temperature and depends on initial conditions. Determination of arc root dimension on the contact has a great significance from various factors point of view as well as of processes after current passage through zero. The calculation starts up from the basic equation for heat conduction

$$\frac{\partial \vartheta}{\partial t} = a\left(\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2}\right) \qquad (1)$$

where x, y, z are coordinates. It is possible to use the method of sources [1], hence after simplification we obtain equation for a stationary arc root

$$\vartheta(r,t) = \frac{2\sqrt{2}U_e I}{c\gamma(4\pi a)^{\frac{3}{2}}} \int_0^{t_z} \frac{\sin\varpi(t_p+t)}{(t_z-t)^{\frac{3}{2}}} \exp\left[\frac{-r^2}{4a(t_z-t)}\right] dt \qquad (2)$$

where r – radius, t – time, U_e – equivalent voltage drop on the electrode, I – current, c – specific heat capacity, γ - specific density, α – temperature conductivity, ω - angular frequency, t_p – time of arcing with respect to the latest supply voltage zero, t_z – time of the current flow. The result presents the temperature distribution for an immovable arc root. Curves of equal temperature are circles. For a moving arc root the curves are of elliptical form.

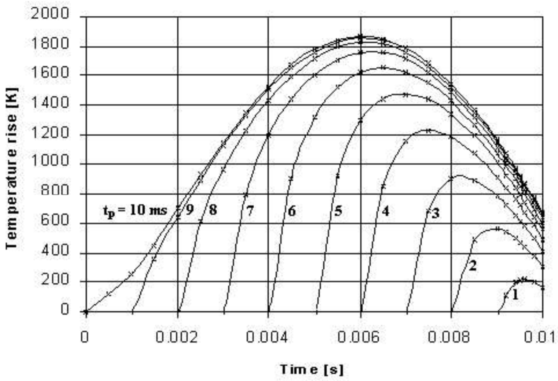

Fig. 1 Temperature rise in an arc root for various times t_p

Thermal energy during the conduction spreads from the place of its origin into the current path and by the process of heat transmission spreads into the surroundings. Temperature in the arc root changes fast, so that it is relevantly convenient to speak of a thermal impulse instead of arcing with some ms time of duration.

Results of calculation show that the diameter of the spot where the temperature achieves the melting or evaporation value depends on various factors. After simplification we can say that the temperature is proportional to the current value.

Calculations were performed for radius 0.3 mm, current r.m.s. value 100 A and for times t_p = 1 – 10 ms, it presents an arcing time t_o = 1 – 10 ms (copper, Fig. 1) [2]. For times t_p >= 4 ms the temperature in the arc root exceedes the value of melting. The diameter of melted material increases with the growth of current value. For higher currents the diameter also increases with evaporation temperature. In the consequence of melting, evaporation and other physical phenomena an increased erosion of contact material is caused.

3. EROSION OF CONTACT MATERIAL

This phenomenon unfavourably influences the life-time of contacts and operational reliability of switchgears. Experimental results show that the erosion of contact materials expressively increases above a certain current value. Nearly 80 % of the material loss has a form of melt. This break point occurs at current value 400 – 700 A. It is valid for copper and materials based on silver alloys (with ingredients: C, CdO, Ni, W) (Fig. 2). For iron the break point is at current value 1000 A .

The analysis shows that 1 - 4 % of breaking arc energy participates on the erosion. This percentage depends on the physical properties of contact material. Copper and silver achieve the upper boundary i. e. 4 % [3]. We can see that it is relatively low value, but the consequences are very expressive (loss of material, deformation of contact surface). In the Fig. 3 we can see the contact surface of materials AgCdO and AgNi after 600 interruptions of current 300 and 1300 A.

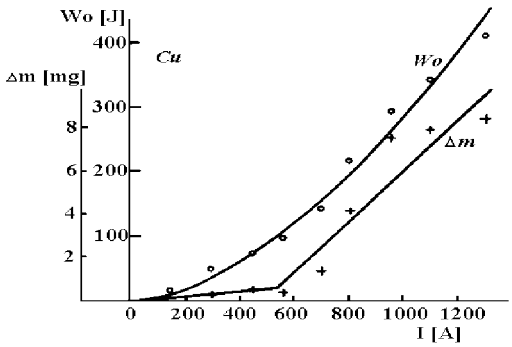

Fig. 2 Arc energy and material loss as function of breaking current

It results from the measurements that it is possible to determine the erosion of contact materials causing energy value the from the loss of contact materials. Hence the equation

$$W_e = K_m \Delta m_m + K_e \Delta m_e \qquad (3)$$

where K_m, K_e are coefficients of energy quantity per melting and evaporation of 1 mg of contact material, Δm_m - loss in the form of melt, Δm_e - loss in the form of vapours. Coefficients K_m, K_e are functions of melting temperature, evaporation temperature, latent heat of melting or evaporation and specific heat capacity [3].

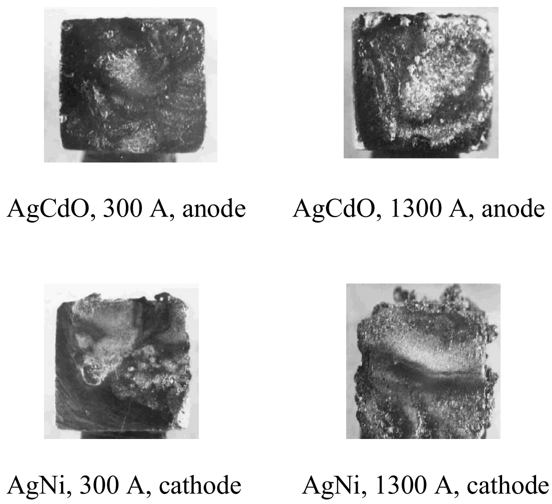

Fig. 3 Contact surface after experiments with currents 300 A and 1300 A

4. CONTACT HEATING IN VARIOUS MODES OF OPERATION

The share of energy at the butt and bridge of contacts on the heating of contact was investigated. The temperature rise of contacts at current breaking with magnitudes within 150 A and 1300 A was measured. The value of accumulated energy was found by calculation. The results show that 50 – 90 % of breaking arc energy is accumulated in the contacts. At small currents (150 A) it is 70 – 90 % and with growth of current magnitude this value decreases down to 50 – 65 %. The temperature increased up to 50 – 60 K [4]. The courses of breaking arc energy *Wo* and accumulated energy into the contacts *Wk* versus current are in the Fig. 4.

In the next experiments the contact heating of contactors were investigated. The result is an energy balance of contactors with rated currents within the limits 6 – 25 A. The breaking of loaded current at switching frequency 1200 per hour shows that the current heating achieves the steady state value of 30 – 40 K. At the every break the temperature rise achieves 5 – 7 K and than decreases due to the heat conduction into the current path. The change of contact resistance changes expressively the time curve of temperature rise. In this case the share of breaking energy is 30 - 40 % of the contact warming. This value also influences the value of load factor [5].

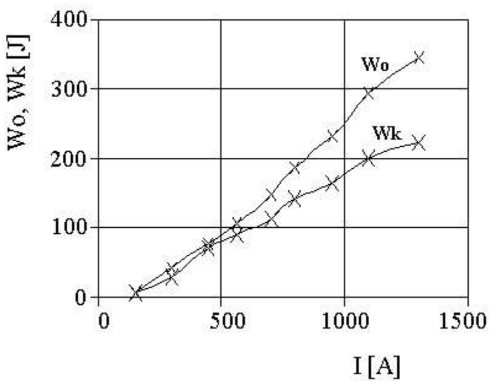

Fig. 4 Arc energy and acumulated energy as fuction of breaking current

Tests of contactors breaking capacity show that the increase of temperature is more expressive, the arc influence is doubled and the temperature rise achieves the value of 10 - 15 K.

From the thermal stress point of view, in subsystems (contacts, extinguishing chamber), it is important where the burning and extinguishing of arc occure. For small currents up to 100 A a system with double current path interruption without the extinguishing chamber is sufficient (typical cases are contactors up to 16 A of rated current) to extinguish arc betwen contacts. For higher currents it is necessary to use extinguishing chamber and to solve the arc motion from the contacts into the chamber. By this way the thermal stress of contact (mainly erosion) decreases and the reliable arc extinction and current interruption is achieved.

The energetic balance and the influence of breaking arc has been investigated for breaking of short-circuit currents with MCB. Magnitudes of short-circuit currents achieve several kA. It is necessary to limit the thermal and dynamical effects of these currents and not to allow a damage of protective device and protective equipment. Current limiting MCB have their characteristics similar to those of fuses, they limit the magnitude of short-circuit current and shorten the time of flowing current down to some ms. Despite of this fact the breaking arc energy achieves several thousands J. The values depend upon design and properties of MCB.

The experimental results show that 60 – 70 % of breaking arc energy is accumulated into the splitters of extinguishing chamber. The measurements were made by calorimetrical method. Measuring temperature rise by thermocouples eliminated sophisticated manipulation and instrumentation. The results achieved by this laboratory method correspond with calorimetrical one. It speeded up and simplified the measurements. This method allows to investigate the temperature rise distribution in one splitter or in more splitters of chamber simultaneously (Fig. 5) [6]. The achieved temperature rise shows 50 – 90 K at current 6 kA and energy value up to 1500 J.

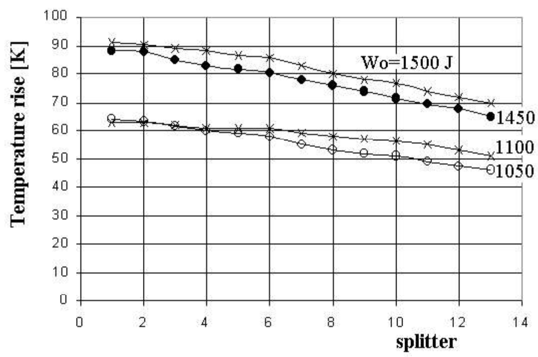

Fig. 5 Temperature rise of metal splitters for various values of arc energy

5. TEMPERATURE OF CURRENT PATH IN STEADY STATE OPERATION

Steady state operation/temperature was investigated with contactors loaded continuously. Temperature distribution in the current path, supposed to be a homogeneous body, is described by Poisson's equation

$$\frac{\partial^2 \vartheta}{\partial x^2} + \frac{\partial^2 \vartheta}{\partial y^2} + \frac{\partial^2 \vartheta}{\partial z^2} = -\frac{\dot{q}}{\lambda} \qquad (4)$$

where ϑ is temperature, x, y, z – coordinates, $\dot{q}$ – generated heat, λ - heat conductivity. Temperature field is a scalar field, analogous to electrostatic and electric fields. Solution of temperature fields is similar to the solution of electrical fields, anyway quantitatively the difference in heat conductivities of metals and insulators are significantly lower than the difference in their electrical conductivities. Hence, they generate considerable heat into the ambient. Shapes of their fields are therefore different but in praxis we can use this analogy and calculate a heat flow according to (by this way reached) simple relations.

Based on the above analogy we can write expressions for thermal resistances, substituting individual parts of the current path. E.g. for a rod with a cross section S and length l it is

$$R_T = \frac{1}{\lambda}\frac{l}{S} \tag{5}$$

and for heat transfer into the ambient it is

$$R_{T\alpha} = \frac{1}{\alpha A} \tag{6}$$

where α - coefficient of heat convention, A – cooling surface.

Based on the above analogy the relation for thermal resistance in the contact is

$$R_s = \frac{ck}{\rho\lambda F^m} \tag{7}$$

where ρ - resistivity, c – corrective coefficient, k – material constant, F – contact force, m – contact type [7].

A switching device is an assembly, a configuration of various heat generating bodies. The heat is conducted into the adjacent parts and transferred into the ambient medium. Individual parts can be replaced by thermal resistances and these can be assembled to a thermal network. The network is solved in a similar way as solved for an electrical network. The result of thermal network solution provides the temperature of the individual network nods (Fig. 6).

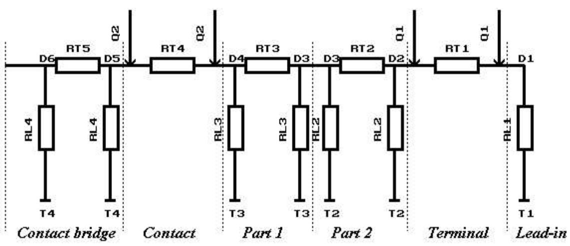

Fig. 6 Thermal network of contactor

The problem of the steady state heat transfer is described in the finite element method by a functional as follows

$$\Pi[\vartheta(x,y,z,)] = \frac{1}{2}\int_V \left(\lambda \left(\left(\frac{\partial \vartheta}{\partial x}\right)^2 + \left(\frac{\partial \vartheta}{\partial y}\right)^2 + \left(\frac{\partial \vartheta}{\partial z}\right)^2 \right) - 2\dot{q}\,\vartheta \right) dV + $$
$$+ \int_{S_2} q\,\vartheta\, dS_2 + \frac{1}{2}\int_{S_3} \alpha(\vartheta - \vartheta_0) dS_3 \tag{7}$$

where: $\vartheta(x,y,z)$ is the unknown temperature field in the body's nods (the volume of the body is V and its surface is S), λ is the isotropic heat conductivity of the material, $\dot{q}$ is the generated heat [W/m^3], q is the conducted heat through the part of the body surface S_2, α is the coefficient of the heat transfer [W/m^{2}K] from the surface area S_3 into the ambient (its temperature is ϑ_0).

By the implementing of the Finite Element Method into the equation (7) an algebraic system of equations is achieved:

$$\mathbf{K}\vartheta = \mathbf{P} \tag{8}$$

$\mathbf{K}$ is the heat transfer matrix, ϑ is the vector of element nod temperatures, $\mathbf{P}$ is the heat loads vector.

To run modeling and simulation experiments on a current path of a part of 100 A electrical switching device, SOLID87 (a 10-nod tetrahedral thermal solid element) from the program ANSYS, version 6.1 [8] was used. The relevant mesh and the resultant temperature field are in Fig. 7 and Fig. 8 respectively [9].

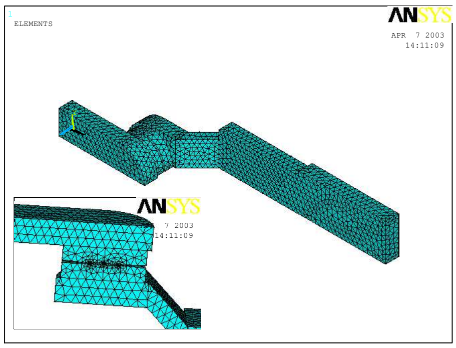

Fig. 7 Mesh of a 100 A current path

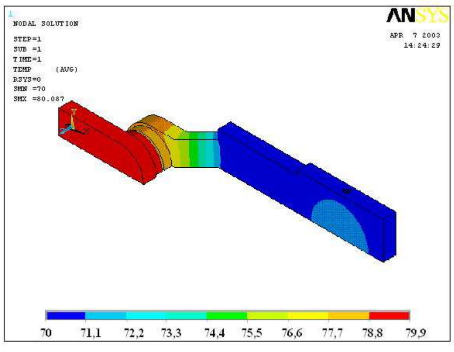

Fig. 8 Temperature field of a 100 A current path

Comparing all the results of analytical and FEM computation with relevant results of temperature measurements gives a good agreement. Comparing the results obtained by thermal nettwork and by simulation with those obtained by laboratory measurements we can see some differences within ±(4 - 6)% of the measured values.

6. CONCLUSION

Generation of considerable quantity of thermal energy is caused by breaking of arc. Quantitatively it depends on the current magnitude, arc voltage and arcing time. The final consequence is the temperature rise. It leads to the thermal stress both in contacts and extinguishing system. Breaking the working currents within 10–100 A causes relatively small increase of temperature rise (from 10^0 to 10^1 K). Breaking the short-circuit currents (e.g. in MCB) causes the temperature rise valued from 10^1 to 10^2 K. In the case when the temperature rise exceedes the permitted value a thermal destruction of insulating materials and failure of electrical devices is supposed.

Knowledge of temperature values over the current path is important from the economical and reliable operation of switching device point of view. Results of measurements and calculations show but small mutual difference in achieved temperature values.

Better and more detailed understanding of temperature field layout, heat flow behaviour and reliable temperature values in the individual spots/nods of interest are enabled by field modelling and simulation mainly.

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BIOGRAPHY

Ľudovít Hüttner was born in 14.9.1946 in Bratislava. In 1969 he graduated Ing. (MSc.) with distinction at the department of Electrical Machines and Devices of the Faculty of Electrical Engineering at Slovak Technical University in Bratislava. He received the PhD. degree from the Slovak Technical University Bratislava in 1988 and there he was also appointed Associate Professor for Power engineering in 1993. Since 1969 he works at the Department of Electrical Machines and Devices. His scientific research is focussed on field of low-voltage electrical devices – thermal and dynamic stress, transient phenomena.