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SOLUTION OF SOME ELECTRICAL DEVICES PROBLEMS BY SIMULATION METHODS

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In the last years, computer simulation has reached a significant position in the investigation and development of technical products. Simulation programmes and computer utilization have found application also in the area of electrical devices. At our workplace we have used simulation programmes for many years to investigate transient phenomena mainly at short-circuit current breaking in miniature circuit breakers (MCB), short faults and forming of surge waves for testing circuit. Computer programmes allow solving difficult tasks of thermal, magnetic and electrical fields, and tasks of mechanical stresses. In the contribution, mainly solutions of some problems in MCB and contactors are presented.

K e y w o r d s: short-circuit current breaking, Joule integral, electric arc, thermal stress, magnetic field, dynamical force

1 INTRODUCTION

In the distribution network of electrical energy, electrical devices play an important part in controlling the energy supply (switching, overcurrent and surge protection *etc*). Its operation must be reliable not only at rated network parameters but at failure case, too. The failure is caused by short-circuit currents and overvoltages when the magnitudes achieve multiples of the rated values. Beside the electrical stress we must calculate with mechanical and thermal stresses. These stresses are decisive from the dimensioning point of view. Particularly for switchgears and protection devices there is a typical phenomenon electrical arc which origins at switching or at fault. The arc is an important thermal source and therefore it is necessary to solve the thermal stress of various parts of the apparatus. These problems must be solved simultaneously because these phenomena are bound together.

2 EQUIVALENCY SOLUTION OF TRANSIENT PHENOMENA AT SWITCHING

The short-circuit current is a typical case of a transient phenomenon in the network. Breaking the short-circuit current is a task of circuit breakers and overcurrent protection devices. For many years we have dealt with problems of MCB, mainly with short-circuit current breaking. MCBs operate as current limiting devices, able to interrupt the short-circuit currents without dangerous consequences. We have been busy with both laboratory and simulation experiments focused on breaking of short-circuit currents by AC miniature circuit breakers.

The operation of a MCB during a laboratory short-circuit current breaking test generates a short-circuit current with tens of kA. The source of the short-circuit current is a synchronous generator or a transformer. Our workplace has such a short–circuit testing laboratory with a generator. However, these tests are time-consuming, laborious and expensive. This is why a laboratory test stand with a series R-L-C circuit has been assembled as a way to substitute it. Now a condenser battery, a capacitor, is a short-circuit current source. The short-current circuit frequency and damping are changed by a proper choice of R, L, C parameters. The current amplitude is defined by the amplitude of the applied voltage.

According to standard requirements and rules, a capacitor test circuit is not allowed for the relevant tests, anyway using it is quite useful both to verify the operation of overcurrent and overvoltage protection devices at short-circuit currents breaking and to run physical experiments with arc extinguishing. To ensure test equivalency of the two circuits it is necessary to adjust the capacitor test circuit in such a way that the current vs time of the two circuits (generator and capacitor source testing circuits) have identical damped harmonic shapes. Mainly the first halfwave in the two circuits must be identical.

It is well known that the current vs time curve is influenced by the arc voltage time dependence or that the design of MCB must cope with network parameters. The time curve and magnitude of the arc voltage depend on the properties of the mechanism and release, fast disconnection of contacts, *ie* , a short opening delay is very important. The arc behaviour is decisively influenced by the aerodynamic conditions in the extinguishing subsystem, force distribution and values in the contact area, contact material *etc* [2].

Analysis of short-circuit current breaking solves the time behaviour of the current in the generator circuit. The simulation code solves the basic differential equation

$$u_s(t) = Ri + L\frac{\mathrm{d}i}{\mathrm{d}t} + u_0 \,. \tag{1}$$

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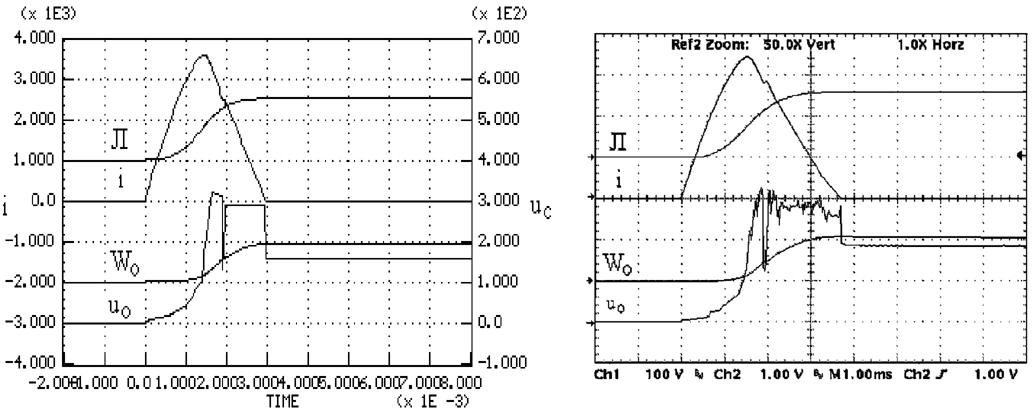

Fig. 1. Short-circuit current breaking: a) results of a simulation, b) oscillogram

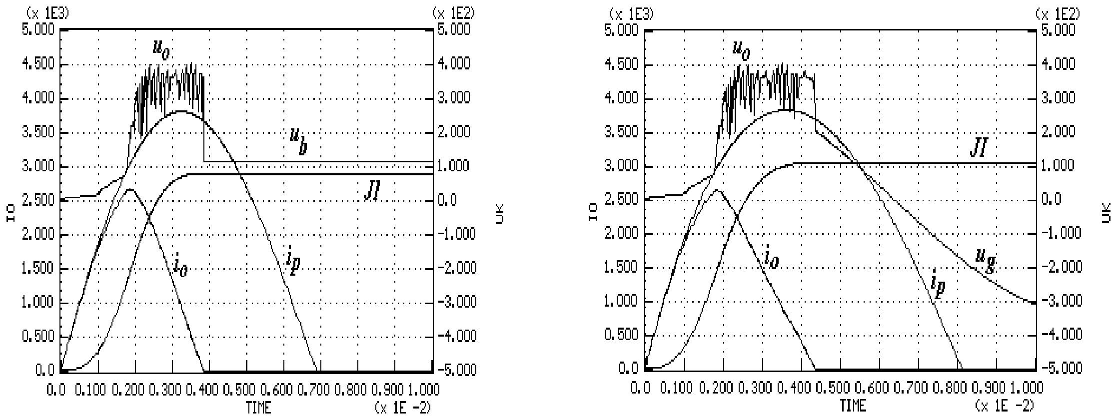

Fig. 2. a) simulation in the circuit with condenser battery: b) simulation in the generator circuit. Legend: u_0 - arc voltage, u_b - condenser battery voltage, i_p - assumed current, i_0 - limited current, J_I - Joule integral

The solution has the form

$$i(t) = \frac{U_m}{Z}\Big[\sin(\omega t + \alpha - \varphi) - sin(\alpha - \varphi)e^{-\frac{R}{L}t}\Big] - \frac{U_0}{R}\Big(1 - e^{-\frac{R}{L}(t-t_1)}\Big) \quad (2)$$

where $u_s(t) = U_m \sin(\omega t + \alpha)$ is the supply voltage, U_m is the amplitude, ω is the angular frequency, α is the initiation instant of the short-circuit current with respect to the foregoing zero value of the supply voltage, φ is the phase shift, R, L are the resistance and inductance of the network, Z is the impedance, t_1 is the time of arc voltage maximum, and U_0 is the arc voltage (constant value). Equation (2) describes the time behaviour of current during interruption of the test circuit supplied with a generator.

Now, a simulation program gives the time behaviour of the limited current for a given time curve of the arc voltage ($u_0(t)$) and the value of the Joule integral ($JI = \int i^2 \mathrm{d}t$), which is of great importance mainly from the breaking capacity and selectivity point of view. In the program, individual parameters can be changed, say the rise time of the arc voltage, magnitude of the arc voltage, to calculate the value of JI and arc energy.

Modelling and simulation experiments with proper programs yield results, displaying dependences that would be very hard to gain in an experimental way. For illustration look at Fig. 1a with the time behaviours of current and voltage at short- circuit breaking.

The arc voltage can be defined very simply as a step function just for very basic studies, later as a data file generated from a real arc voltage behaviour obtained from experiments (Fig. 1b).

For a capacitor test circuit the following basic equation is valid

$$\frac{1}{C}\int i\mathrm{d}t - U_{C0} + Ri + L\frac{\mathrm{d}i}{\mathrm{d}t} + U_0 = 0 \quad (3)$$

where U_0 is the arc voltage, R, L are the resistance and inductance of the circuit, C is the capacitance of the condenser battery, U_{C0} is the voltage of the charged condenser battery. Solution is in the form

$$i(t) = \frac{U_{C0}}{\omega_0 L}e^{-\frac{R}{2L}}\sin(\omega_0 t) - \frac{U_0}{R}\Big(1 - e^{-\frac{R}{L}(t-t_1)}\Big), \quad (4)$$

$$\omega_0 = \sqrt{\frac{1}{LC} - \Big(\frac{R}{2L}\Big)^2} \quad (5)$$

where ω_0 is the angular frequency.

Comparing equations (2) and (4) we see that the first components are the assumed currents in the circuits for

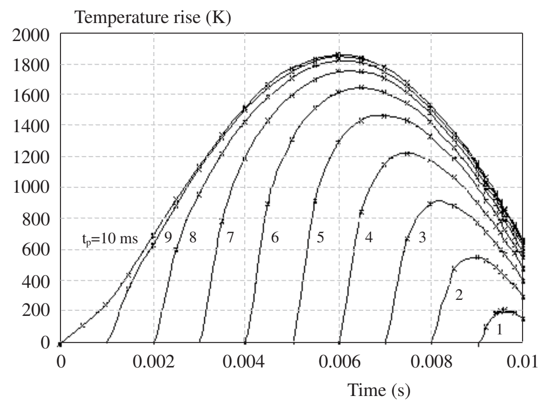

Fig. 3. Temperature rise in the arc root

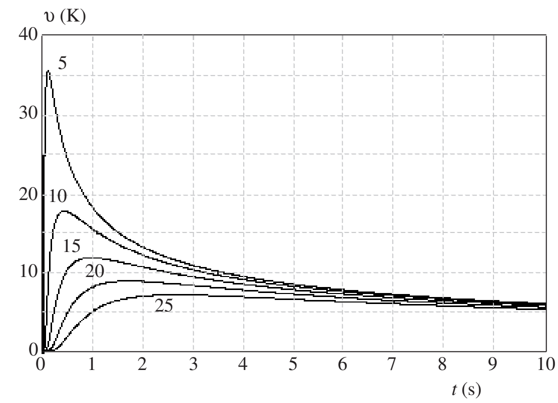

Fig. 4. Temperature distribution at thermal impulse in the copper contact

$U_0 = 0$. The second components are identical and represent the influence of the arc voltage. Evidently, the amplitude of the arc voltage affects the voltage drop and deformation of the interrupted short-circuit current.

In the generator circuit the current-time behaviour depends on the value of angle α. Measurements at various angles α are required for tests according to standard. The change of angle is performed by a programmable device. Analysis of equation (2) shows that the most unfavourable cases are within $40-80°$. It means that in the capacitor test circuit a proper choice of element parameters and setting of the required time behaviour of current for a given angle α in the generator circuit is necessary. Input parameters are: amplitude of the assumed current and length of the first halfwave. The amplitude of capacitor battery charging voltage is approximately equal to the amplitude of the generator voltage.

In our laboratory, capacitor battery test circuits are used to generate high currents and to investigate the properties of MCB and other electrical devices at short-circuit currents breaking. Therefore it is very important for us to know that the tests of the short-circuit current breaking with our capacitor test circuit are equivalent to those in the generator supplied test circuits.

The results of simulation experiments show that the current shapes within the relevant interval are almost identical, *ie* , the instant differences of the Joule integral $\int i^2 \mathrm{d}t$ are minimal (Fig. 2). The Joule integral is a measure of the transferred energy and classifies MCB from the selectivity class point of view. The breaking process is short and the current behaviour at the breaking is deformed by the arc voltage. From this point of view it is possible to say that the tests in both test circuits give equivalent results.

For the developed testing circuits, parameters were found by simulation for tests of overvoltage protective devices. According to standards these devices are tested with a voltage and current surge wave with defined parameters. For voltage wave $1.2/50\,\mu$s and current waves $8/20\,\mu$s and $10/350\,\mu$s the values of circuit elements were determined in dependence on the charging voltages.

3 SOLUTION OF THERMAL PROBLEMS

The electric arc is a strong thermal source. Thermal energy is accumulated into the parts of the contact and extinguishing systems. The outcome is overheating of these parts and pressure changes. The breaking arc during the short-time transient regime is an intensive thermal source and leads to a resolute increase of temperature in the arc root. Theoretical investigation of this process yields the temperature of the contact. The temperature is a function of time and space coordinates.

The calculation comes out from the basic equation for heat conduction in the solid body

$$c\rho\frac{\partial\vartheta}{\partial t} = \frac{\partial}{\partial x}\Big(\lambda\frac{\partial\vartheta}{\partial x}\Big) + \frac{\partial}{\partial y}\Big(\lambda\frac{\partial\vartheta}{\partial y}\Big) + \frac{\partial}{\partial z}\Big(\lambda\frac{\partial\vartheta}{\partial z}\Big) \tag{7}$$

where ϑ is temperature, c is the specific heat, ρ is the density, λ is the heat conductivity, and x, y, z are coordinates. If we assume that $\lambda = \text{const}$, then

$$\frac{\partial\vartheta}{\partial t} = a\nabla^2\vartheta \tag{8}$$

where a is the temperature conductivity.

Solution of this thermal field yields a time-space distribution of temperature and depends on the initial conditions. Determination of arc root dimensions on the contact has significance from the points of view of several factors as well as of processes after current passage through zero. Calculation is based on the basic equation for heat conduction. It is possible to use the method of sources [3] and after simplification we have the equation for a stationary arc root

$$\vartheta(r,t) = \frac{2\sqrt{2}U_e I}{c\rho(4\pi a)^{3/2}}\int_0^{t_z}\frac{\sin\omega(t_p+t)}{(t_z-t)^{3/2}}\exp\Big(\frac{-r^2}{4a(t_z-t)}\Big)\mathrm{d}t \tag{9}$$

where r is the radius, t is time, U_e is the equivalent voltage drop on the electrode, I is current, c is the specific heat, ρ is the density, a is temperature conductivity, ω is the angular frequency, t_p is the time of arcing with respect to the previous supply voltage zero, t_z is

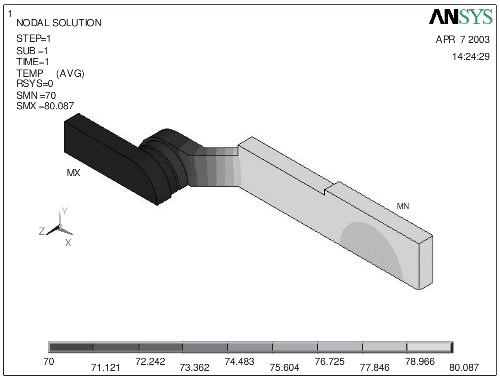

Fig. 5. Temperature field in the current path

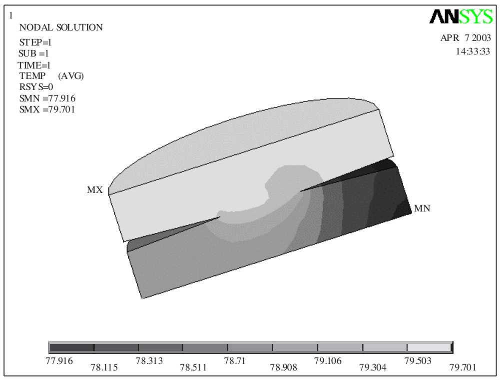

Fig. 6. Temperature field in the contact area

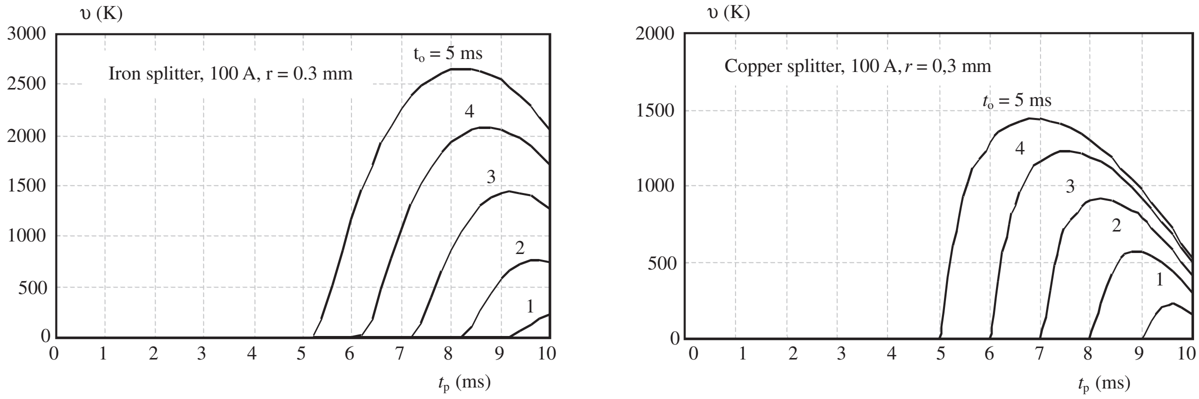

Fig. 7. Temperature distribution in the copper and iron splitters

the time of current flow. The result presents the temperature distribution for an immovable arc root. The curves of equal temperature are circles. For a moving arc root the curves have elliptic shapes. The temperature in the arc root changes fast and we can speak about a thermal impulse in the place of arcing with duration of several milliseconds.

The results of calculation show that the diameter where the temperature achieves the melting or evaporation value depends on various factors. With simplification we can say that the temperature is proportional to the current value. Calculation was solved for radius 0.3 mm and current r.m.s. value 100 A and for times $t_p = 1$ to 10 ms, which presents the arcing time $t_0 = 1$ to 10 ms (copper, Fig. 3) [4]. For times $t_p \geq 4$ ms the temperature in the arc root exceeds the melting point. The diameter of melted material increases with the growth of current. For higher currents the diameter increases with evaporation temperature, too. As a consequence of melting, evaporation and other physical phenomena, erosion of the contact material increases. This is a case of an arc created on interrupting short-circuit currents with values of several thousands amperes.

As a consequence, the thermal impulse from the arc burning on the contact is the source of heat conducted out and overheating the contact holders and other parts of the path of current. It is possible to solve the temperature distribution by means of the basic equation for heat conduction (8). Calculation of the temperature distribution has been solved for a copper contact with dimensions $10.5 \times 1.5 \times 30$ mm and thermal impulse 20 W (Fig. 4). On the basis of the results, a method has been developed for determining the energy accumulated in the contact [5].

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

$$\Pi\left[\vartheta(x,y,z)\right] = \frac{1}{2}\left[\int_V \lambda\Big(\big(\frac{\partial\vartheta}{\partial x}\big)^2+\big(\frac{\partial\vartheta}{\partial y}\big)^2+\big(\frac{\partial\vartheta}{\partial z}\big)^2-2\dot{q}\vartheta\Big)\mathrm{d}V + \int_{S_2} q\vartheta \mathrm{d}S_2 + \frac{1}{2}\int_{S_3}\alpha(\vartheta-\vartheta_0)\mathrm{d}S_3\right] \quad (10)$$

where $\vartheta(x,y,z)$ is the unknown temperature field in individual points of the body (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 heat transfer [W/m^{2}K] from the part of surface S_3 into the ambient, and ϑ_0 is the ambient temperature.

After implementation of the finite element method into equation (10) [6] an algebraic system of equations is achieved:

$$\mathbf{K}\vartheta = \boldsymbol{P}\,. \quad (11)$$

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

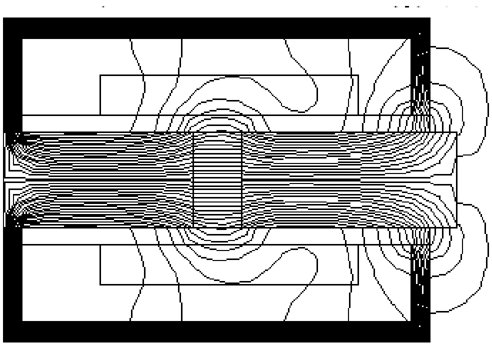

Fig. 8. Map of magnetic field of electromagnetic release

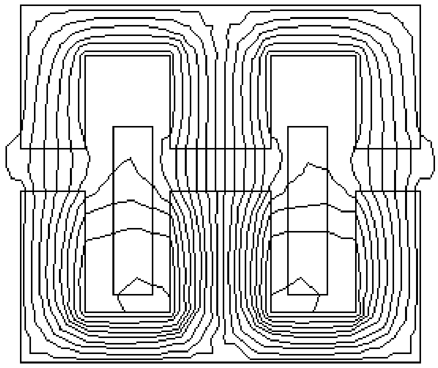

Fig. 9. Map of magnetic field of contactor electromagnet

For modelling of the current path, the SOLID87 — a 10-nodal point tetrahedral thermal solid element of program ANSYS, version 6.1 [7] has been used. The obtained temperature field of the 100 A electrical switching device is given in Fig. 5. A detail of the temperature field in the contact area is given in Fig. 6 [8].

After arcing between the contacts it is necessary to direct the arc motion into an extinguishing chamber. The arc in the chamber is divided to partial arcs between the splitters — the accumulated energy causes overheating of the splitters.

The time-space distribution of temperature can be solved by means of the method of sources. Tajev's equation (9) can be used for this calculation, too. The expression is valid for a stationery arc root on a metal splitter. Calculations of temperature distribution have been made for copper and iron splitters (Fig. 7). Calculation has been conducted for radius 0.3 mm and current r.m.s. value 100 A and for times $t_p = 5$ to 9 ms, which represents the arcing time $t_0 = 5$ to 1 ms. It is evident from the curves that the temperature rise depends on the material properties. The temperature rise for a longer arcing time (5 ms) exceeds the evaporation temperature [9]. This process leads to the erosion of splitters. The low value of thermal conductivity of iron causes a doubled increase of temperature rise in comparison with copper. For a smaller radius and stationary arc this ends in an increase of temperature up to the temperatures of melting and evaporation.

For a moving arc root the relations are other and even more complicated. Therefore it is convenient to use Tajev's work [3] and the temperature rise can be calculated as

$$\vartheta(r,t) = \frac{2\sqrt{2}U_e I}{c\rho(4\pi a)^{3/2}} \int_0^{t_z} \left[\frac{\sin\omega(t_p+t)}{(t_z-t)^{3/2}} \times \exp\Big(\frac{-(x-vt)^2+y^2+z^2}{4a(t_z-t)} \Big) \right] \mathrm{d}t \quad (12)$$

where v is the velocity of the arc root, x, y, z are coordinates of the investigated point. In the case of a stationary arc the lines with constant temperature are circles, in the case of moving arcs the shape of these lines is distorted and they are similar to ellipses.

In the case of metal splitters as parts of the extinguishing chamber we have to remember that the breaking arc is divided in partial arcs and this creates two thermal sources on every splitter. The thickness is usually 1 mm and the final temperature distribution is given as a superimposition of both thermal sources. Both arc roots are in motion. The time curve of current is distorted and limited by the arc voltage.

4 SOLUTION OF MAGNETIC FIELD AND CALCULATION OF FORCES

The solution of magnetic fields in electrical devices is a difficult problem. There are fields generated by current flow through the current path and the result is dynamical forces. Then we can calculate the mechanical stress, mainly at short-circuit currents. The force is given by the Biot-Savart law

$$\mathrm{d}\overline{F} = i \int \mathrm{d}\bar{l} x \overline{B}\,. \quad (13)$$

On the other hand it is necessary to know the values of magnetic variables in the magnetic circuit of actuators — various electromagnets in the contactor and relay and an overcurrent release in a circuit breaker and MCB [10].

The operation of releasing an overcurrent is a function of both the overload and short-circuit currents. The release produces an impulse introduced into the mechanism of the devices on achieving the preset value of current. The electromagnet must produce a sufficient force to release the mechanism lock. The force is given by equation (13) and for this case it is

$$F = 4B_\delta^2 \delta \varepsilon 10^5 + 1.67 F_m \frac{S}{l_c} \quad (14)$$

where B_δ is the flux density in the air gap, δ is the length the air gap, S is the armature cross section area, ε is a coefficient, F_m is the number of ampere-turns, l_c is the length of coil.

Mutual coupling between the magnetic field and the electrical circuit is given by the law of flow

$$\oint \overline{H} \mathrm{d}\bar{l} = Ni \quad (15)$$

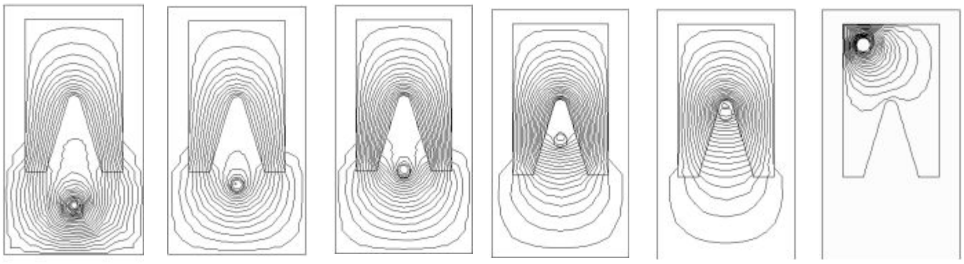

Fig. 10. Map of magnetic field for various position of arc

where H is field intensity, l is the average length of induction lines, N is the number of turns, i is the current.

The properties of the electromagnet must provide achievement of the required tripping characteristic. Optimization of the electromagnetic release is influenced by more factors, such as the position of the coil, the size of the air gap, material and dimensions of the magnetic circuit. To form a prescribed tripping characteristic the number of turns for a given size of the air gap has to be solved. The magnetic field has been solved as a magnetostatic problem for a constant permeability (Fig. 8).

To design a contactor electromagnet, the required value of tractive force and size of the air gap are given parameters. Dimensions of the magnetic circuit and of the coil must be designed so that the flux density does not exceed the predetermined value. In Fig. 9 there is a map of the magnetic field.

We have solved the problems of arc extinguishing in the chamber with metal splitters of MCB for many years. After contact opening the arc is removed into the space under the chamber. The arc is affected by dynamical forces and aerodynamical conditions in the extinguishing and contact subsystems. The influence of metal splitters and the force on the arc is very interesting. It is described by the equation

$$\overline{F}_y = \frac{1}{2} i \Big(\frac{\partial \Phi_y}{\partial y} \Big) \tag{16}$$

(16) where Φ_y is the magnetic flux, y is a coordinate.

The magnetic flux is generated by the current flowing through the arc. The force depends on the arc shape and its position. The arc under low-voltage has a random shape and cross-section and, therefore, for our simulation it has been assumed to have a circular form with a diameter of 2 mm. In Fig. 10, the map of the magnetic field in various positions of the arc can be seen.

5 CONCLUSION

The use of computers and simulation programs allows solving theoretical problems, optimization of device design, support of development, fast solution of various operating states, change/choice of materials and dimensions *etc*. The solution is obtained in a graphical form as a map of the field, dependence of various variables (flux density, mechanical force, torque, gradient of temperature, voltage *etc*).

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