MODELING AND SIMULATION OF THE THERMAL STRESS AT THE ELECTRIC FUSES CONTACTS

A. Baraboi*, I. Ciutea**, M. Adam*, C. Pancu*, T. A. Baraboi***
«Gh. Asachi» Technical University*,
National Company of Electricity**, Artinfo Co.***
Iasi-Romania

Abstract: An electrical RC or R model of the thermal process, with numerical EMTP treatment and results concerning the thermal stress at the electric fuses contacts are presented.

0 INTRODUCTION

Electric fuses are protection apparatus with the role to limit current and power in electrical circuit when is crossed by an overcurrent or a short-circuit current.

Also, at the first sight the electric fuse manufacture and its working principle don't seen a hardly gain insight into matters, in fact, this device working is complex [1], [7], [8].

Its working must be considered like a logical succession, from cause to effect, by many different kind processes (electrical, thermal, sometime mechanical processes, etc) which unfold in different ways. These processes can be investigated like transient condition (states), in certain period of times or, interesting for their space localization, at a given moment.

Proceeding from working principle, fuse elements must have minimum thermal stability in the protected circuit, so that, under overcurrents or short-circuit currents action, the circuit switching off must be done inside electric fuse during a limited time.

Working fuse means melting fuse element during a limited time, which takes place at a fixed temperature. The heating conduction, giving off by Joule-Lenz effect into fuse element, leads to temperature increasing in different manufactured parts, closes or farther by fuse link.

During on working fuse, the conduction heating transmission thermal flux reaches component parts closes or farther by thermal source-fuse link, depending on current intensity which brings about fuse working.

At short-circuit currents, the thermal processes are adiabatically and, so, the temperature increasing is located on fuse link, where specific losses through electrical-thermal effect are maximum.

In the case of normal condition or overload currents, when working period of times are bigger, the temperature increasings because of fuse link heating reach peripherical manufactured parts such as, for instance, the electic fuse contacts.

The electric fuse contacts heating depends on current and fuse features, so, working time. On the other hand, the electric contacts are thermal sources themselves. The contacts technical condition influences their temperature and fuse link temperature, so, fuse working characteristics.

Making evident these aspects is possible to use an adequate model to fuse working and a software to allow numerical simulation of a thermal transmission complex model, not depending on transient or permanent conditions.

1 ELECTRICAL MODEL OF THE THERMAL PROCESS

II.1 Theory on the RC modeling

The electrical modeling of thermal processes makes possible thermal transmission analyse both in transient and permanent conditions.

Table I – Thermal conduction equation

Coordinate system	Equation
Cartesian	$p=\gamma c\frac{\partial\theta}{\partial t}-\lambda_x\frac{\partial^2\theta}{\partial x^2}-\lambda_y\frac{\partial^2\theta}{\partial y^2}-\lambda_z\frac{\partial^2\theta}{\partial z^2}$
Cylindrical	$p=\gamma c\frac{\partial\theta}{\partial t}-\lambda\left(\frac{\partial^2\theta}{\partial r^2}+\frac{1}{r}\frac{\partial\theta}{\partial r}+\frac{1}{r^2}\frac{\partial^2\theta}{\partial\varphi^2}+\frac{\partial^2\theta}{\partial z^2}\right)$
Spherical	$p=\gamma c\frac{\partial\theta}{\partial t}-\lambda\left(\frac{\partial^2\theta}{\partial r^2}+\frac{2}{r}\frac{\partial\theta}{\partial r}+\frac{1}{r^2\sin\vartheta}\frac{\partial^2\theta}{\partial\varphi^2}+\frac{1}{r^2 tg\vartheta}\frac{\partial\theta}{\partial\vartheta}+\frac{1}{r^2}\frac{\partial^2\theta}{\partial\vartheta^2}\right)$

The giving of heating by Joule-Lenz effect into volume of conduction material crossed by current is continuously transported from warmer temperature zones to smaller value temperature zones.

The heating transfer in the solid materials takes place by conduction.

This phenomenon is ruled by Fourier law which allow to establish the general equation of thermal conduction in transient conditions.

In accordance to coordinate system to use, this equation can have one of shown formula from Table I, [4], [5].

The notations mean: p-specific losses from Joule-Lenz effect; θ-temperature; γ-density, c-specific heating; λ-thermal conductivity; x, y, z-cartesian coordinates; r, φ, z-cylindrical coordinates; r, φ, θ-spherical coordinates.

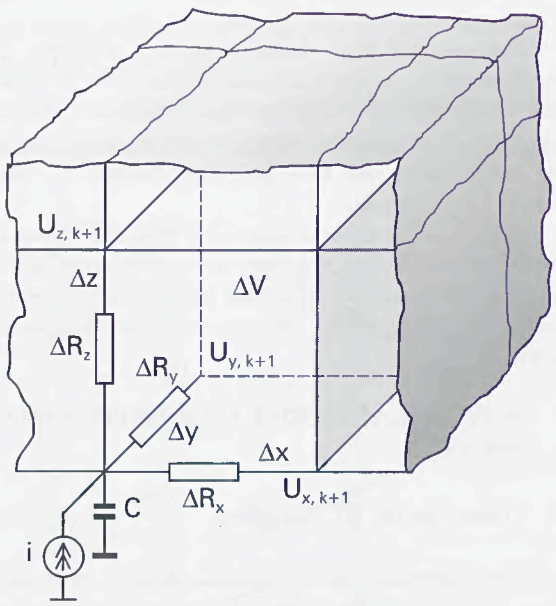

Fig.1 Electrical RC model of the thermal transmission into elementary volume

If thermal conduction refers to an elementary volume ΔV (Fig.1), using finite differences method, first equation from Table I, it gets:

$$p=\gamma c\left.\frac{d\theta}{dt}\right|_k-\lambda_x\frac{\theta_{x,k-1}-2\theta_k+\theta_{x,k+1}}{(\Delta x)^2}-\\-\lambda_y\frac{\theta_{y,k-1}-2\theta_k+\theta_{y,k+1}}{(\Delta y)^2}-\lambda_z\frac{\theta_{z,k-1}-2\theta_k+\theta_{z,k+1}}{(\Delta z)^2} \quad (1)$$

where: $\theta_{k,k-1}$, θ_k, $\theta_{k,k+1}$ are recorded temperatures in three successive points to x, y, z directions.

Equation (1) may be written under next form:

$$\frac{\Delta P}{2}=\frac{\Delta m}{2}c\left.\frac{d\theta}{dt}\right|_k+\frac{\theta_k-\theta_{x,k-1}}{\Delta R_{tx}}+\frac{\theta_k-\theta_{x,k+1}}{\Delta R_{tx}}+\\+\frac{\theta_k-\theta_{y,k-1}}{\Delta R_{ty}}+\frac{\theta_k-\theta_{y,k+1}}{\Delta R_{ty}}+\frac{\theta_k-\theta_{z,k-1}}{\Delta R_{tz}}+\frac{\theta_k-\theta_{z,k+1}}{\Delta R_{tz}}, \quad (2)$$

where it was noted:

$$\Delta V=\Delta x\Delta y\Delta z,\ \Delta P=p\Delta V,\ \Delta R_{tx}=\frac{2\Delta x}{\lambda_x\Delta y\Delta z},\\ \Delta R_{ty}=\frac{2\Delta y}{\lambda_y\Delta x\Delta z},\ \Delta R_{tz}=\frac{2\Delta z}{\lambda_z\Delta x\Delta y}, \quad (3)$$

Starting from correspondence relationships:

$$\frac{\Delta P}{2}\Leftrightarrow i,\ \frac{\Delta m}{c}\Leftrightarrow C,\ \Delta R_t\Leftrightarrow \Delta R,\ \theta\Leftrightarrow u \quad (4)$$

it can simulate the thermal conduction into volume ΔV using electrical equivalent network RC with the electrical circuit, [6], shown in Fig.1.

The Joule-Lenz effect losses into considered volume are modeled using current source i. If the volume ΔV not represent an electrical-thermal conversion headquarters, then this current source is missing from equivalent circuit.

Refering to physical reasons it is necessary that at heating transmission describing to add initial and limit thermal conditions at considered model.

Regarding to initial conditions could be considered under next form:

$$\theta(x,y,z,0)=\theta_0(x,y,z)\Leftrightarrow u_k(0)=u_{k0}. \quad (5)$$

About limit conditions if environment temperature has constant and known values it supposes that thermal changing are ruled by Newton law.

The thermal resistance ΔR_{ts} of changing surface is modeled by an adequate resistance ΔR_s connected to equivalent electrical circuit of reference conductor, meaning environment temperature:

$$\Delta R_{ts}=\frac{1}{\alpha_t\Delta S}\Leftrightarrow \Delta R_s=\frac{1}{\alpha_t\Delta S}. \quad (6)$$

In the relation (6), ΔS means thermal changing surface and α_t-global coefficient of heating transfer.

The electric contact presence on analysed conductor is considered by its supplementary power contribution:

$$\Delta P_c=R_c(\Delta i)^2, \quad (7)$$

where R_c is contact resistance, [2] and Δi means current fraction which crossed conductor.

II.2 EMTP simulation program

Thermal stresses simulation of electrical equipment using EMTP logical programming has the advantage to solve electrical circuits into transient conditions.

In this way it is possible to make the connection from cause to effect in the case of Joule effect electrical-thermal conversion of energy.

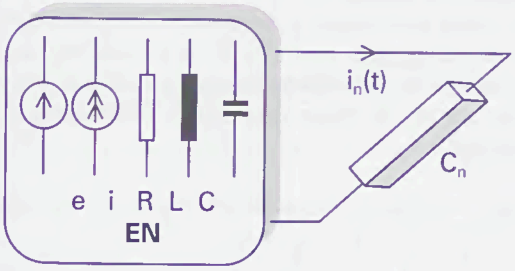

Fig. 2 Electrical network with thermal processes

In Fig.2 is shown the simulation object materialized through conducting section C_n crossed by current in(t), which belongs to electrical network EN.

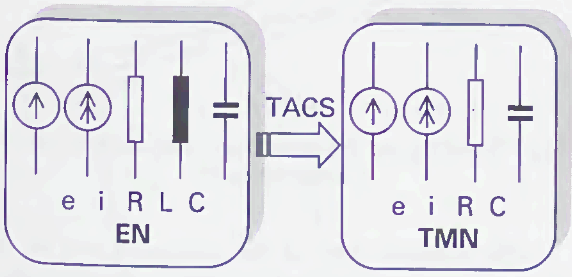

Fig.3 EMTP connection of the TMN thermal model to EN electric network

With the possibility to make analogue models using TASC, EMTP allow to cause-effect sense connection of TMN network, which means electrical model of thermal processes, to proper electrical network, EN (Fig. 3). So, it is possible the simulation of thermal processes inside conductor because of Joule effect under current actions to any electrical conductions.

This kind of model in a practical using entails to go over following stages:

a) to make a scale drawing of studied reference point;
b) to make partitions into modeled reference point volume, so that will be divided in elementary volumes by Δx, Δy, Δz sizes;
c) to any elementary volume i attaches a knot n where converge thermal resistance from those three directions and thermal capacity. It gets electrical model of thermal processes like a RC network which it solves using EMT Program in the transient conditions.

As it can notice, the stages b) and c) request a very laborious hardworking so, from this reason, it searched for a better solution to solve automatically these stages and, implicitly, to generate the simulation EMTP software.

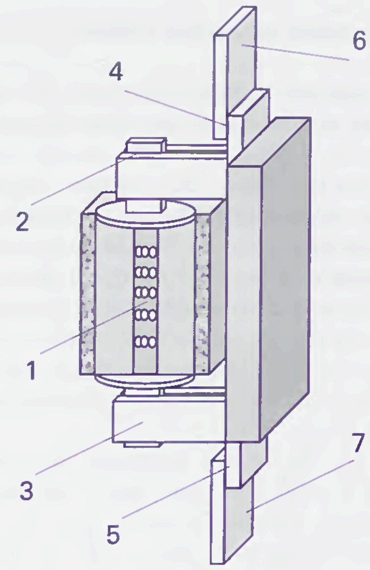

Fig.4 Modeled rapid fuse

The automation drawing up of EMTP simulation software can make using an one s own software named «RC Network» by authors. This software is achieved using Turbo Pascal language to IBM PS compatible computers. The software structure is a conversational type, input date are introduced into windows which contain enough information about processes.

After compiling, «RC Network» software achieves a file with a name given by user. This file means just EMTP solve program of EN-TMN networks which supplies voltages in different knots of analyse reference point like output data.

2 NUMERICAL TREATMENT. RESULTS

III.1 Construction of modeled electric fuse

There have been modeled the thermal states of a fast low-voltage electric fuse type like in Fig. 4. The fuse element 1 is an unique band of copper. On the fuse conducting path were considered contacts 2 and 3 of the replacing element and 4 and 5 of the socket. At these ones, are linked the conductors 6, 7, each one with a length of 1m.

Using «RCNetwork» program, were generated EMTP files of more than 1800 lines, for the numerical simulation of both steady (resistive circuits) and transient (RC circuits) thermal states.

The resistivity of the metals on the conducting path traversed by current in fuse working, was considered linear variable with the temperature.

We preferred to use at it's maximum the TACS capability for electric modeling of thermal processes, in order to prove the contacts thermal stress.

That's why the heating current was considered with it's effective values, independent of the simulated thermal state.

III.2 Steady states numerical results

We simulated the thermal stress for the steady working state of a fuse with the value of the current of 125 A.

The thermal state of electric contacts was simulated by the heat from the contact resistance. This, and the values of the current traversing the electric fuse and its contacts were parameterized. For the comparison was considered the ideal case, with a null contact resistance.

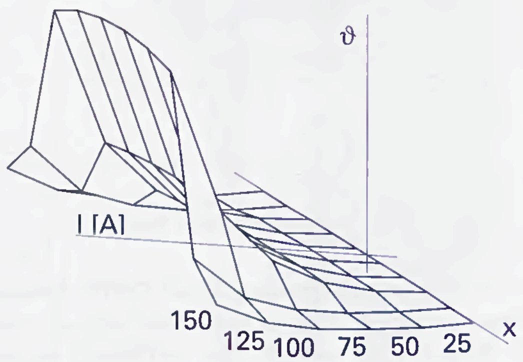

Fig.5 Over-temperatures in thermal steady state

Fig.5 presents the repartition of the over-temperatures in steady state, computed on the conducting path, for different values of the current. The contacts are considered ideal, with null contact resistance.

The influence of the contacts over the thermal state of the fusible element is illustrated in Fig.6, where is presented the repartition of the steady state temperature, computed for an 125 A current and for different given values of the contact resistance R_c.

The values of the contact resistance are influencing the thermal state of both the fusible element and the contact.

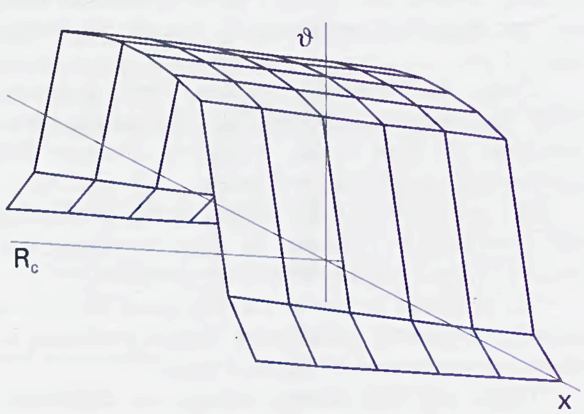

Fig.6 Influence of the contact resistance

That's why for 20 mV voltage falls over the fuse's contacts, that are normal for its working state, their temperature reaches 75 °C. If the voltage fall is of 100 mV, when the contact is damaged, the over-temperature for the steady state is of 117 °C. If we take into account the influence of temperature on mechanical properties of the metal, [3], those temperature fluctuations can be corrected.

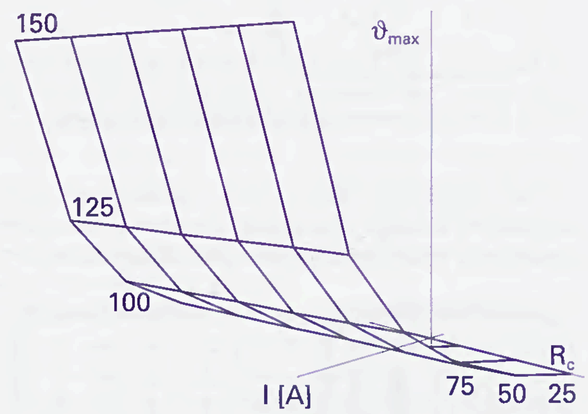

Fig.7 Steady state maximal over-temperature of the fusible element

The technical state of the contacts, given by the value of the contact resistance is influencing the thermal state of the fusible element. In Fig.7 are showed curves obtained from the computing of the maximal over-temperature in steady state from the central part of the fusible element, function with the values of the contact resistance, for different values of the current. If in the steady nominal state (I=125 A), for 20 mV voltage falls on contacts, the maximal computed over-temperature of the fusible element is of 212 °C, after the contacts technical state alteration, considering for the same current voltage falls of 100 mV, arises a rise of the maximal over-temperature of the fuse at 253 °C. The supplementary contacts heating due to their technical state, are influencing through the maximal temperature of the fusible element, the melting time and the fuse's time-current characteristic.

III.3 Numerical results concerning the transient states

The electrical model of the thermal process that takes place at the transient state fuse working is an RC network with more than 1700 branches, with their nodes.

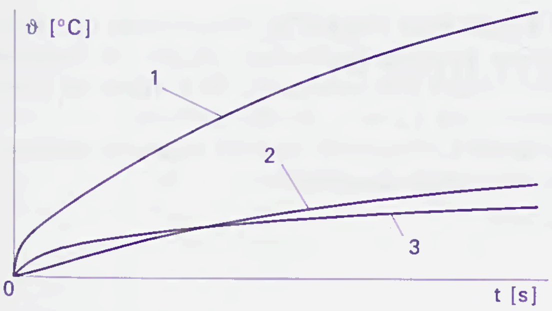

Fig.8 Over-temperatures in transient state

This allows the monitoring of the transient thermal response for an random shape of the current traversing the fuse. In this case this was considered step.

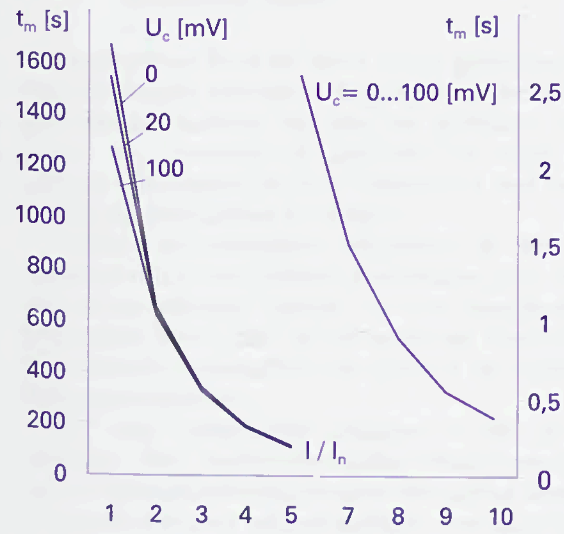

Fig.9 Influence of the electric contacts state on the melting time-current characteristic

In Fig.8 is presented the transient state of the over-temperature, in the case of nominal working current (125 A), localized in the area of the fusible element (curve 1) with the biggest temperature on the contacts of the replacing element (curve 2) and of the socket (curve 3). The contact resistance values are for a normal technical state characterized by 20 mV voltage falls.

The excesive heating of the contacts is transmitted to the fusible element and causes the lowering of it's melting time. This fact is illustrated in Fig.9, that contains the time-current characteristics computed with our model.

We observe that at the rise of the contact resistance, big influences over the melting durations appear only at low overcurrents. As the current rises, the heat propagation becomes more restricted, because the thermal processes are more and more adiabatic ones.

3 CONCLUSIONS

The RC electric circuits modeling of the conductance thermal transmition allows the using of EMTP for the numerical simulation of the thermal transient states.

We propose a software that allows the automatisation of the EMTP files replacement, and makes possible a fast way of building complex models with thousands of branches and nodes. There are electrically modeled the thermal phenomena that appear in a fast low voltage fuse, and there are analised the reciproc influences between the fusible element and the contacts.

There are presented results of the numerical simulationof the steady state, and there is emphasised the rise of the maximal fusible element over-temperature as the contacts thermal state becames worse.

These results are orienting the analysis of the transient states towards the problem of the influence of the contacts technical state over the time-current fuse characteristic.

There is emphasized the lowering of the fusion time due to the overheating of the conductor in the contact zones, fact that introduces errors in the fuse's time-current characteristic.

The model allows the analysis of any transient or permanent processes, directly or indirectly influenced by the thermal states of the fusible element and of the contacts.

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