ANALYSIS OF THERMAL PHENOMENA IN HIGH-VOLTAGE FUSE-LINKS

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Abstract: There are presented the main results obtained by numerical simulation of temperature distribution in fuse-links, considering adiabatic and non adiabatic process for heat flow in fuse-elements and in fuse-link, respectively. Results were used for development of a new series of fuse-links for motor starting circuits of 7.2 kV, 25... 250 A.

I. INTRODUCTION

High-voltage fuses for motor circuit protection have been continually developed, in general on the basis of experimental methods. Because the processes which govern the operation of fuse-link are many and complex, its analysis is very complicated and several simplifying assumptions are required.

Analysis of temperature distribution in the fuse-elements with a non-uniform cross-section area, in the case of an adiabatic process, is very important for determining some parts of the prearcing time-current characteristics, especially in the region of the extremely short prearcing times.

The very complicated situation is that of the prearcing times longer than those which correspond with an adiabatic process, because the current densities in the fuse-elements are not constant over their cross-section or along their lengths due to the presence of the restrictions. In addition, resistivity increases as the fuse-element temperature rises, and the effects of various component parts, like fine-grain filler, outer body, end caps, conecting cables must be considered in temperature distribution.

Numerical methods are very useful to determine the temperature distribution for adiabatic and non adiabatic process, and were applicated with succes in our works in developing a new series of high-voltage fuse-links for motor circuits protection, [1].

II. ANALYSIS OF TRANSIENT AND STEADY-STATE TEMPERATURE DISTRIBUTION

The processes which govern the heat movement in a fuse-link are very complex, except the case of the very short prearcing times, when there is an adiabatic process.

An overall model, which allows to compute the temperature distribution in the fuse-link from the extremely short prearcing times to long prearcing times must consider the heat generated within the fuse-elements by Joulean heating, wich is lost axially by conduction to the end caps and radially by conduction through the filler and fuse-link body and then by radiation and convection from the body and end caps.

Application of numerical methods for such a simulation conducts to a number of simplifying assumptions, [2]. The finite-difference method, using the Crank-Nicholson approximation and succesive overrelaxation, [3], [4] was used for the transient and steady-state temperature distribution, [5], [6].

The temperature distribution in fuse-elements, in the case of an adiabatic process, is governed by the equation:

$$\frac{\rho(\theta)j^2}{\lambda} = -\left[\frac{\partial^2\theta(x,y)}{\partial x^2} + \frac{\partial^2\theta(x,y)}{\partial y^2}\right] + \frac{c\gamma}{\lambda}\frac{\partial\theta(x,y)}{\partial t} \quad (1)$$

where:

- θ temperature of element [°C]
- $\rho(\theta)$ resistivity [Ωm]
- c specific heat [Ws/kg°C]
- λ thermal conductivity [W/m°C]
- γ density of material [kg/m^3]
- j current density [A/m^2]

The left term corresponds to the heat generated in the fuse-elements and the right term represents the sum of the heat lost by conduction within the fuse elements and the heat stored in the elements. If the prearcing times are very short, the term coresponding to the heat lost by conduction is practically zero and entire energy generated in elements is used for rise the temperature of the elements. Fig. 1 represents the scheme used for numerical simulation of temperature distribution, in the case of an adiabatic process, which refers only to the fuse-elements, with a certain form of restriction. The shape of restriction is very different from a firm to another, depending on the imagination of engineers, but all fuse-elements must satisfy the conditions imposed for motor type fuse-links, to have a "fast-slow" prearcing time-current characteristics, that is the operation should be as rapid as possible on heavy faults and to resist indefinitely under repeated starting conditions of motors.

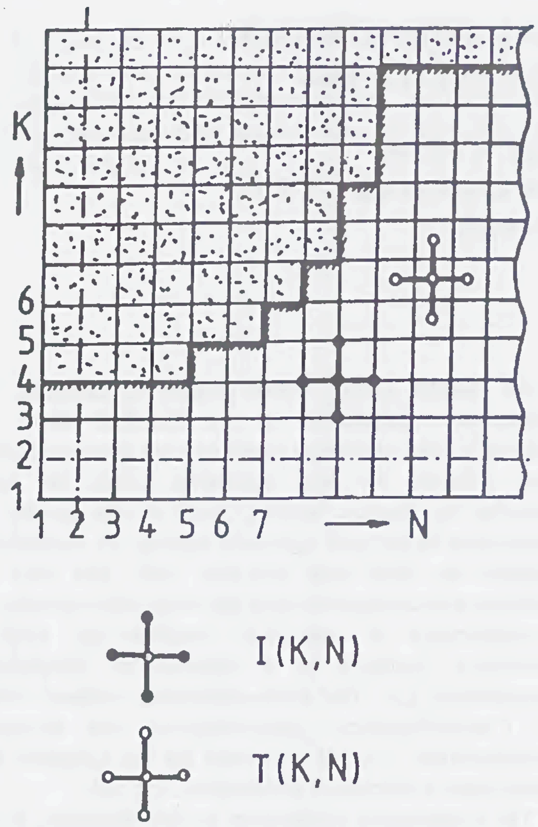

Fig.1 Finite-difference mesh for an adiabatic process analysis

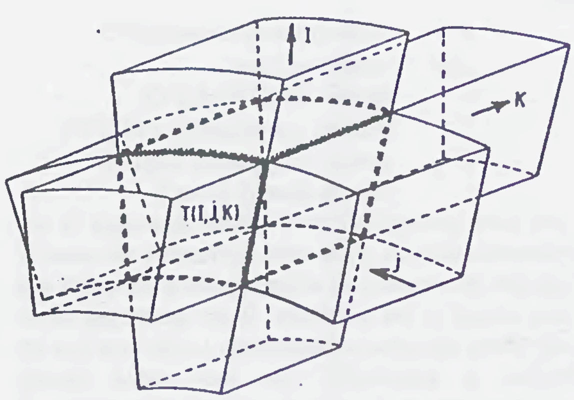

Fig.2 Spatial subvolumes used in the case of a non adiabatic process analysis

It can be seen that there are two grids, one for current distribution, and another one for temperature distribution. Using the Crank-Nicholson approximation and extrapolated Liebmann method of succesive overrelaxation, the temperature of a subvolume (k,n) at (w+1)th iteration, after determination of the current density by numerical differentiation, can be computed with following equation:

$$T^{w+1}(n,k) = (1-\alpha).T^{w}(k,n) + \alpha.T5 \qquad (2)$$

where:

w – order of iteration

α – accelerating factor of convergence; the value of α lies between 1 and 2;

T5 – a general term, depending on temperatures of the subvolumes adjacent to the subvolume (k,n) and the flow of energy generated within the subvolume (k,n).

In the case of a non adiabatic process analysis, used for a 3D simulation of temperature distribution in all parts of the fuse-link, the scheme is that of Fig.2 and the terms corresponding to the heat lost from the body of fuse-link by convection and by radiation must be added to equation (1). For calculation it was utilised only a part of fuse-link, like that in Fig.3, with two axis of symmetry, one in fuse-element and another at the middle distance between two fuse-elements

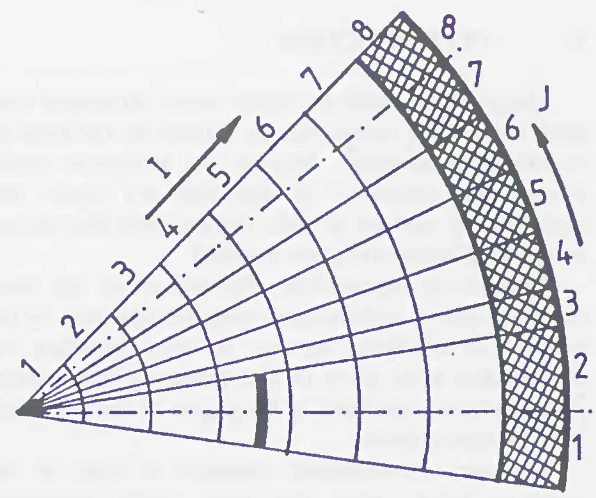

Fig.3 A cross-section in a part of fuse-link, with two axis of symmetry

At each time step Δt, a specified number of iterations were executed, to determine the steady-state temperature distribution inside the fuse-link, taking into account that the heat is transmitted only in radial direction in the filler, because of relatively high length/diameter ratio. The values obtained were used as initial conditions for the next time step. For the heat transmission from the external surface of the body of fuse-link having temperature T(i,j,k), to the ambient air having temperature T_{amb} must be considered the transmission by radiation and by convection.

Heat transmitted by radiation Q_r is obtained using:

$$Q_r = 5.77 S c_r (T_1^4 - T_a^4)\Delta t \qquad (3)$$

where:

S – external surface of fuse-link

c_r – coefficient of radiation

T_1 = [T(i,j,k)+273]/100

T_a = [T_{amb}+273]/100

Heat transmitted by convection Q_c is obtained using:

$$Q_c = \lambda_a S[T(i,j,k) - T_{amb}]\Delta t \qquad (4)$$

where:

$\lambda_a = 33\ d^{-0.625}$ coefficient of transmission by convection, for laminar flow of air

d – characteristic dimension of fuse-link (diameter)

The values for coeficients c_r and λ_a were established on the basis of a great number of test in laboratory, for determinig temperature-rise limits of fuse-links.

III. COMPUTATIONAL RESULTS AND COMPARISON WITH TEST RESULTS

Fig.4 shows a temperature distribution obtained by finite-difference method, in the region of a restriction of the fuse-element used for fuse-link of 7.2 kV, 250 A.

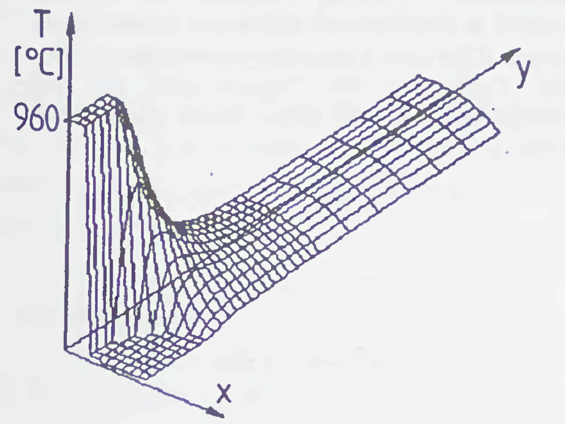

Fig. 4 Temperature distribution calculated in fuse-element (adiabatic process)

It can be seen the strong difference between the temperature of restriction area in comparison with the rest part of fuse-element. The difference between the calculated time necessary to obtain the melting temperature of the fuse-element and the measured time obtained in high breaking capacity is about 10%, which is an acceptable value.

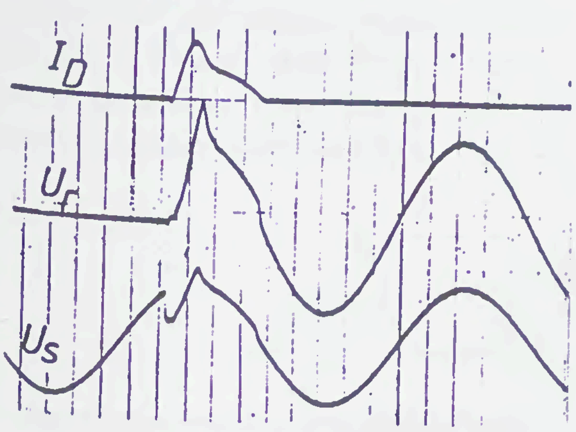

Fig.5 Oscillogram obtained at test duty 1 for a fuse- link 7.2 kV, 100 A

Fig.5 represents an oscillogram obtained in high power laboratory, test duty 1 with a prospective current testing of 31.5 kA_{ef} for a fuse-link of 7.2 kV- 100 A. It must be pointed out the small value of transient recovery voltage, due to the adequate number of restrictions, with a shape wich allows the cooling of the electric arc.

Table 1 shows the measured (t_m) and calculated (tc) values of time necessary to attain the temperature-rise $\Delta\theta$, in a test for determining the temperature-rise limit (steady-state regime) at a rating current of 250 A. The differences between these values are in the range of ± 10%.

Table 1 Measured and calculated time for attain certain value of temperature-rise, at test with rated current of 250 A

t_m [s]	3000	7500	12000	15600	16200	21600
$\Delta\theta_1$ [°C]	42	56	57	58	58.5	60
t_{c1} [s]	3100	6700	11990	15100	15800	21550
$\Delta\theta_2$ [°C]	26	58	64	66	66.5	68
t_{c2} [s]	2650	7600	12900	15950	16560	23600

$\Delta\theta_1$= temperature-rise at end cap

$\Delta\theta_2$= temperature-rise at the middle of fuse-link

In Table 2 are shown measured and calculated values of the energy disipated by convection Q_c and by radiation Q_r, for a medium temperature-rise $\Delta\theta$ of the external surface of the fuse-link. , in the case of testing with rating currents and the currents coresponding to the withstand tests, [7]. The difference between these values can be accepted in practice and this calculation eliminates a great number of long and expensive tests in laboratory.

The determination of factor K require a great number of expensive tests, to sequence no.1 (100 cycles of 1 h) and sequence no.2 (2000 cycles of 10 min.). The dificulty for fuse-elements consists not in withstanding the value of the current but in providing corresponding flexibility to take up thermal cycling associated with the starting requirements of motors.

Table 2 Measured and calculated values for energy disipated from external surface of fuse-link

Testing type	Rating current testing		Withstand testing	
	I_n [A]		I_n [A]	
	100	250	100	250
$\Delta\theta$ [°C]	32	68	18	32
Q_c [W]	23	59	11.4	23.4
Q_r [W]	23	57	9.9	20.4
Q_{tc} [W]	46	116	21.3	43.8
Q_m [W]	44	112	20.8	43.52

$Q_{tc}= Q_c+ Q_r$ (calculated) Q_m (measured)

For example, the same fuse-element, used for a fuse-link of 125 A rating current, subjected to 115 cycles of sequence no.1 failed after 720 cycles of sequence no.2, for a factor K=0.65 but resisted to 110 cycles of sequence no.1 and 2500 cycles of sequence no.2, for K=0.6.

This type of thermal stress is very important and must be taken into account in determination of final constructive solution for fuse-element.

IV CONCLUSIONS

The calculation of the temperature distribution in fuse-element and in fuse-link has been confirmed the validity of the method, in comparison with experimental investigations, and has been used for development of a new series of fuse-links for motor circuit applications, U_n=7.2kV, In=25...250 A.

The differences between the measured and calculated values of temperature-rise, time to attain a certain value of them or between energy dissipated by fuse-links are normally, because of the assumptions made in calculation.

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