NEW ASPECTS ON THE MULTI-ELEMENT FUSE PROTECTION CHARACTERISTIC

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Abstract: The fuses protection characteristics can be improved also by replacing the single way current fuse with two or more parallel connected fuses.
In our paper we proposed a mathematical model for an ensemble of two fusible elements, connected in parallel, in order to determine the protection characteristic of the ensemble for a specific load. .
Based on this mathematical model, we will be analyzed the case of two symmetric and asymmetric fuse ensemble, also the possibility to control the current distribution on each fusible element.
The mathematical and experimental results lead to some new information about the multi-element fuse protection characteristic with arguments for the asymmetric fuse construction.
The results obtained permit to make some technical and economical evaluation for the multi-element fuses construction and functioning in electrical circuit protection.

I. INTRODUCTION

The improvement performances of the fuses is an up-to-date preoccupation which provides solutions concerning their conception and structure, the materials used or the geometry of the fusible element.

This paper proposes an approach focused on the functioning of the multielement fuses during the pre-arch stage for the situation where the fusible elements are identical and different, respectively.

On may come to interesting conclusions regarding the protection characteristic of the multielement fuses and also regarding the influence of the asymmetry degree on their functioning during the pre-arch stage for (2-4) I_n.

I. THE SYMMETRICAL MULTI-ELEMENT FUSE BEHAVIOR DURING THE PRE-ARCH STAGE

The fusible element diameter for a fuse with nominal current I_n , can be determinate using the relation:

$$\lambda \cdot I_n = kd^{\frac{3}{2}}, \tag{1}$$

the fusible diameter being:

$$d_0 = \sqrt[3]{\frac{\lambda^2 I_n^2}{k^2}} \text{ , [mm]}, \tag{2}$$

where, if the fusible element material is copper, the constants are : $\lambda = 1.6$ and $k = 60$, respectively .

If we consider the overload currents in the domain of (2-4) I_n , it can be accepted, as a first approximation, that the over-temperature evolution in time takes place conform to the expression:

$$\vartheta(t) = \vartheta_{max}(1-e^{-\frac{t}{T_0}}), \tag{3}$$

practically definite by the maximum overtemperature ϑ_{max} and the thermal time constant T_0 ,

$$\vartheta_{max} = \frac{4\rho I_n^2}{k_t \pi^2 d_0^3}, \qquad T_0 = \frac{\gamma c d_0}{4k_t}, \tag{4}$$

where, in the relation (3) and (4) , $\rho[\Omega m]$ represents the material resistivity of fusible element, $\gamma[Kg/m^3]$ is the density of the fusible material, $c[J/kg^oC]$ is the specific heat, and $k_t[w/m^2\ ^oC]$ is the global heat transfer coefficient .

For an over-current passing through the fuse equal with λI_n , the over-temperature of the element, see (4), becomes:

$$\vartheta_{max} = \frac{4\rho\lambda^2 I_n^2}{k_t \pi^2 d_0^3} = \vartheta_{top}, \tag{5}$$

and the melting time for the fusible element is considered to be:

$$t_0 = 4T_0 \ , \tag{6}$$

If we consider the over current to be $m\lambda I_n$, the relation (4) become:

$$\vartheta_{max} = \frac{4\rho\lambda^2 m^2 I_n^2}{k_t \pi^2 d_0^3} = m^2 \vartheta_{top} \ , \qquad m>1, \tag{7}$$

and the melting time for the fusible element, t_{0m} is determined by the solution of the equation:

$$\vartheta_m(t_{0m}) = \vartheta_{max}(1 - e^{-\frac{t_{0m}}{T_0}}) = \vartheta_{top} . \quad (8)$$

Solving the equation (8) the melting time will be:

$$t_{0m} = T_0 \ln\frac{m^2}{m^2 - 1} , \quad (9)$$

When instead of a single fusible element we use two identical elements connected in parallel , their diameter will be:

$$d_1 = \sqrt[3]{\frac{\lambda^2 I_n^2}{4k^2}} = d_0\frac{1}{\sqrt[3]{4}} , \quad (10)$$

Taking into account the relation (4_2), the thermal time constant in this case become:

$$T_1 = \frac{\gamma c d_1}{4k_t} = T_0\frac{1}{\sqrt[3]{4}} , \quad (11)$$

Considering the over-current going through these two symmetrical fusible elements equal with λI_n , the biggest value of the over-temperature is :

$$\vartheta^*_{max1} = \frac{4\rho\lambda^2(\frac{I_n}{2})^2}{k_t\pi^2 d_0^3\frac{1}{4}} = \vartheta_{top} = \vartheta^*_{max} , \quad (12)$$

thus, the melting time of the first fusible element (practically of both elements in symmetrical construction) is considered to be :

$$t_1 = 4T_1 = 4T_0\frac{1}{\sqrt[3]{4}} \le t_0 , \quad (13)$$

value that is smaller with 33.79% than the value of t_0 according to the case of the fuse with a single fusible element , see (6).

In this case for the over-current value $m\lambda I_n$, the expression (4_1) become:

$$\vartheta_{max\ m,1} = \frac{4\rho\lambda^2 m^2(\frac{I_n}{2})^2}{k_t\pi^2 d_0^3\frac{1}{4}} = m^2\vartheta_{top} , \quad (14)$$

thus, the time when the first element melts and practically the circuit breaking occur, t_{m1}, is the solution of an equation like (8), resulting :

$$t_{1m} = T_1 \ln\frac{m^2}{m^2 - 1} , \quad (15)$$

it's value being smaller than the value of t_{0m} with about 33.8 %.

Therefore, we can affirm that the protection characteristic for a fuse with two identical fusible elements in parallel is situated under the protection characteristic according to a fuse with a single fusible element for the overcurrents rage between (2-4)I_n , even if the hypothesis imposed for the analytical approach of the proposed model (the current considered is constant, the neglecting the distribution of the temperature along the fusible element and the variation of material parameters with the temperature) are not fit for the real functioning conditions of the fuses.

II. THE ASYMMETRICAL MULTI-ELEMENT FUSE BEHAVIOR DURING THE PRE-ARCH STAGE

The construction of the asymmetric multi-element fuses requires, the substitution of the fusible element with diameter d_0 corresponding to the nominal current I_n , by two fusible elements, with different diameters, corresponding to the nominal current I_{n1} , respectively I_{n2} .

One may write the following expressions:

$$I_n = I_{n1} + I_{n2} \ , \ I_{n1} = \alpha I_n \ , \alpha < 1/2$$
$$I_{n2} = (1-\alpha)I_n \ , \ I_{n1} < I_{n2} . \quad (16)$$

The two fusible element diameters will be:

$$d_1' = d_0\alpha^{\frac{2}{3}} \ , \ d_2' = d_0(1-\alpha)^{\frac{2}{3}} , \quad (17)$$

and the expressions of thermal time constants became:

$$T_2' = (1-\alpha)^{\frac{2}{3}}T_0 \ , \ T_1' = \alpha^{\frac{2}{3}}T_0 \quad (18)$$

If the multi-element fuse is passing by the over-current λI_n the relation (5) is:

$$\vartheta^{(1)}_{max} = \frac{4\rho\lambda^2 I_n^2\alpha^2}{k_t\pi^2(d_0\alpha^{\frac{2}{3}})^3} = \vartheta_{top}$$

$$\vartheta^{(2)}_{max} = \frac{4\rho\lambda^2 I_n^2(1-\alpha)^2}{k_t\pi^2(d_0(1-\alpha)^{\frac{2}{3}})^3} = \vartheta_{top} . \quad (19)$$

The temperature evolution of the fusible elements takes place in according to an expression like (3), but because $T_1' < T_2'$ the smaller diameter element will melt first after a time τ_1 that can be evaluated with the expression:

$$\tau_1 = 4T_1' = 4T_0\alpha^{\frac{2}{3}} \quad , \qquad (20)$$

at this moment the other fusible element will have the following over-temperature:

$$\vartheta_2'(\tau_1) = \vartheta_{top}(1-e^{-\frac{\tau_1}{T_2}}) = = \vartheta_{top}(1-e^{-4(\frac{\alpha}{1-\alpha})^{\frac{2}{3}}}) \qquad (21)$$

From this moment the entire current λI_n will pass only through the fusible element with diameter d_2' , so that, from that moment the overtemperature evolution in time will be determinate by the relation:

$$\vartheta_2''(t) = \vartheta_2'(\tau_1) + +[\vartheta''_{\max 2} - \vartheta_2'(\tau_1)](1-e^{-\frac{t}{T_2'}}) \quad , \qquad (22)$$

where:

$$\vartheta''_{\max 2} = \frac{1}{(1-\alpha)^2}\vartheta_{top} > \vartheta_{top} \qquad (23)$$

The other fusible element will melt (and the circuit breaking) will appear after the time τ_2 which can be recalculated from the equation:

$$\vartheta_2''(\tau_2) = \vartheta_{top} \quad , \qquad (24)$$

thus we obtained:

$$\tau_2 = T_2' \ln \frac{\frac{1}{(1-\alpha)^2} - 1 + e^{-4(\frac{\alpha}{1-\alpha})^{\frac{2}{3}}}}{\frac{1}{(1-\alpha)^2} - 1} \quad . \qquad (25)$$

The functioning time of the asymmetric multi-element fuse will be:

$$t_2 = \tau_1 + \tau_2 = T_0[4\alpha^{\frac{2}{3}} + +(1-\alpha)^{\frac{2}{3}} \ln \frac{\frac{1}{(1-\alpha)^2} - 1 + e^{-4(\frac{\alpha}{1-\alpha})^{\frac{2}{3}}}}{\frac{1}{(1-\alpha)^2} - 1}] \qquad (26)$$

depending on the asymmetry degree α.

In order to emphasize the influence of the asymmetry degree on the breaking time of the multi-element fuse for an over-current λI_n , we will consider the function:

$$f(x) = 4x^{\frac{2}{3}} + +(1-x)^{\frac{2}{3}} \ln \frac{\frac{1}{(1-x)^2} - 1 + e^{-4(\frac{x}{1-x})^{\frac{2}{3}}}}{\frac{1}{(1-x)^2} - 1} \quad , \qquad (27)$$

with $\qquad 0 < x < 1/2$

it's evolution being represented in Fig. 1.

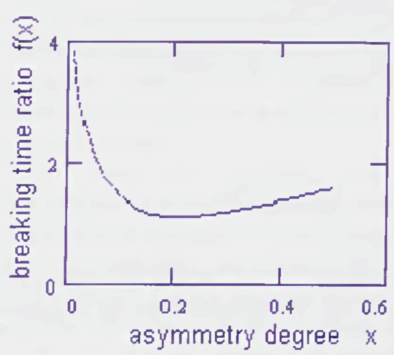

Figure 1. The influence of the asymmetry degree on the breaking time ratio.

Fig.1 emphasizes a point of minimum for the function f(x) for a value of asymmetry degree, that indicate a decreasing of the fuse's pre-arch time in the overload currents domain. Also, the maximum value of the function f(x) is:

$$f(x) < 4 \qquad (28)$$

The minimum fuse breaking time is:

$t_{2min} = 1.126T_0$, for the asymmetry degree $x = 0.215$

Comparing this with the single element fuse, the asymmetric multi-element fuse provides a relative decreasing of the pre-arch time with about 71.8 %.

When the multi-element asymmetric fuse function at the current $m\lambda I_n$, with m>1, the maximum values of the fusible element over-temperatures will be:

$$\vartheta'_{\max 1m} = \vartheta'_{\max 2m} = m^2\vartheta_{top} \quad , \quad m>1 \qquad (29)$$

The melting time for the thinner element τ_1 is obtained from the equation:

$$\vartheta'_{1m}(\tau') = m^2\vartheta_{top}(1-e^{-\frac{\tau_1'}{T_2}}) = \vartheta_{top} \, , \qquad (30)$$

resulting:

$$\tau_1' = T_1' \ln\frac{m^2}{m^2-1} = \alpha^{\frac{3}{2}}T_0 \ln\frac{m^2}{m^2-1} \, , \qquad (31)$$

The value of the other element over-temperature (with diameter d'_2) at the moment τ'_1 is:

$$\vartheta'_{2m}(\tau'_1) = m^2\vartheta_{top}(1-e^{-\frac{\tau'_1}{T'_2}}) = \\ = m^2\vartheta_{top}(1-e^{-(\frac{\alpha}{1-\alpha})^{\frac{2}{3}}\ln\frac{m^2}{m^2-1}}) < \vartheta_{top} \tag{32}$$

The over-temperature evolution of the second element passing through by the current $m\lambda I_n$ is:

$$\vartheta''_{2m}(t) = \vartheta'_{2m}(\tau'_1) + \\ +[\vartheta''_{\max 2m} - \vartheta'_{2m}(\tau'_1)](1-e^{-\frac{t}{T'_2}}) \tag{33}$$

obtaining:

$$\vartheta''_{\max 2m} = \frac{m^2}{(1-\alpha)^2}\vartheta_{top} \tag{34}$$

The time τ'_2 , when the second fusible element melts can be obtained from the equation:

$$\vartheta''_{2m}(\tau'_2) = \vartheta_{top} \tag{35}$$

the time τ'_2 will be:

$$\tau'_2 = T'_2 \ln \frac{\frac{1}{(1-\alpha)^2} - 1 + e^{-(\frac{\alpha}{1-\alpha})^2}}{\frac{1}{(1-\alpha)^2} - \frac{1}{m^2}} \tag{36}$$

The total function time for the asymmetric multi-element fuse is:

$$t_{2m} = T_0[\alpha^{\frac{2}{3}} \ln\frac{m^2}{m^2-1} + \\ (1-\alpha)^{\frac{2}{3}} \ln \frac{\frac{1}{(1-\alpha)^2} - 1 + e^{-(\frac{\alpha}{1-\alpha})^{\frac{2}{3}}\ln\frac{m^2}{m^2-1}}}{\frac{1}{(1-\alpha)^2} - \frac{1}{m^2}}] \tag{37}$$

Taking into consideration the function g(x,m) described by the relation:

$$g(x,m) = x^{\frac{2}{3}} \ln\frac{m^2}{m^2-1} + \\ +(1-x)^{\frac{2}{3}} \ln \frac{\frac{1}{(1-x)^2} - 1 + e^{-(\frac{x}{1-x})^{\frac{2}{3}}\ln\frac{m^2}{m^2-1}}}{\frac{1}{(1-x)^2} - \frac{1}{m^2}} \tag{38}$$

it's evolution can be represented in Fig.2.

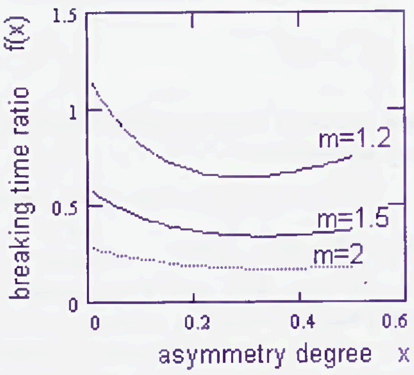

Figure 2. The influence of the asymmetry degree on the breaking time ratio for different values of factor m.

Figure 2 emphasize a minimum for the fuse breaking time ratio curves depending by the factor m, minimum that is more accentuated then the value of factor m →1, which correspond to an optimal design for multi-element asymmetric fuses from the point of view of the asymmetry degree. The minimum for the breaking time ratio correspond to x = 0.29÷ 0.35.

For example, for m = 1.2 and I= $m\lambda I_n$, the multi-element fuse breaking time decrease with 45.85 %, comparing with a single fusible element fuse.

III. EXPERIMENTAL RESULTS

The validation of the analytic results has been obtained by means of the device as the one presented in Fig.3 which permits the fixation of the number of fusible elements, identical or different, their connection in parallel and the supply assembly from an adjusting power supply.

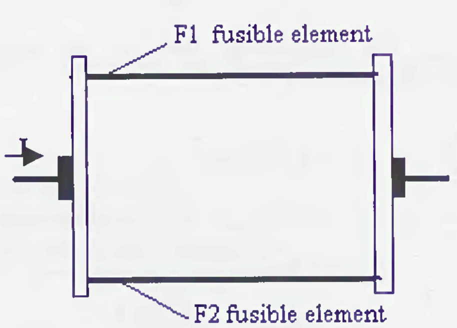

Figure 3. Multi-element fuse

The nominal current is I_n = 15 A, so that the melting current is λI_n = 25 A. We have been made tests for over-currents up to 100 A. The conductors diameters of the multi-element fuse are presented in Table 1.

Table 1- Fusible element diameters

d_0 [mm]	d_1 [mm]	d_2 [mm]	d_3 [mm]
0.56	0.35	0.3	0.4

In the case of the multi-element fuse we take into account different lengths in order to keep the currents distribution on the two ramifications.

The installation scheme is shown by Fig. 4 and the results of the experimental tests are given in Fig.5.

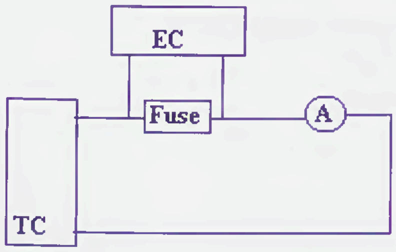

Figure 4. Experimental installation scheme
TC – current power supply
EC – electronic chronometer
A – ampermetre

If we compare the curve corresponding to a single fusible element with the one obtained for the symmetrical bi-element construction, we will notice that the reducing of the functioning time, in the domain of pre-arch, is about 30%, fact which confirm the analytic results.

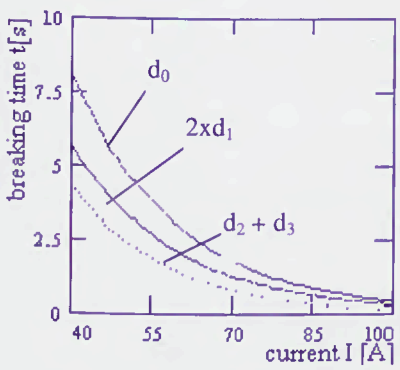

Figure 5. Experimental diagram

If we take as reference the curve corresponding to a single fusible element and we compare it to the one resulted for the asymmetrical bi-element fuse having the asymmetry degree x = 0.4, we will observe a marked reducing of the functioning time in the pre-arch domain with about 70%, in concordance with the analytic results.

IV. Conclusions

The paper proposes a model for the functioning analysis of the multi-element fuses in the over-current regime taking as reference a construction with a single fusible element which is compared with symmetrical and asymmetrical fuses variants.

In the case of symmetrical bi-element fuses the experimental results concerning the functioning time reducing (about 30 %), confirm the analytical ones which indicate for the breaking time a reducing ratio about 33.8 %.

We may also notice a reducing of the functioning time of the asymmetrical bi-element fuse, a reducing which depends on the asymmetry degree. For the asymmetrical bi-element fuse having the asymmetry degree x = 0.4, we will observe a reducing of the functioning time in the pre-arch domain with about 71.8 %, in concordance with the experimental results which indicate a reducing with about 70 %.

It is to be mentioned the concordance of the experimental results with the analytical ones, though the hypothesis considered in the elaboration of the model may be meliorated.

An important observation regarding the functioning of the asymmetrical multi-element fuses relies on the dependence of the melting time on the asymmetry degree. Has been obtained minimum values for the breaking time which emphasize an optimal domain for the asymmetry degree α (α = 0.2÷0.35), values which are different from the ones that are indicated in the literature [1].

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