COMPARISON OF SYNTHETIC AND DIRECT TESTING OF MINIATURE FUSES

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ABSTRACT

According to IEC publication 127 the breaking capacity of miniature fuses should be tested using a voltage source of sufficient power. In the past proposals have been made and experiments have been carried out to test the breaking capacity of such fuses in an LC-circuit. It can be argued that relevant conditions in an LC-circuit differ from those as experienced in a direct test method, especially during the arcing period.

Starting from a simplified arcing model the paper presents arguments based on which it becomes conceivable that direct testing may result in different conditions in both test methods, which may lead to test results which are not comparable with each other.

1. INTRODUCTION

The breaking capacity of a miniature fuse is at least determined by two criteria, viz [1]

1-1 The maximum arc power which in general is developed at the instant of fusing.
1-2 The arc energy W_b generated in the fuse during the arcing period.

In this paper a comparison will be made between two methods of testing the breaking capacity of miniature fuses, viz, direct testing according to IEC publication 127, and synthetic testing in an LRC-circuit, as proposed several times in litterature e.g. by Winter at all [2]. Assuming the validity of both above mentioned criteria then the two testing methods should result in equal results with respect to the criteria mentioned and under otherwise comparable circumstances as e.g. pre-arcing conditions.

So we confine ourselve to the arcing period and to the question whether a synthetic test circuit can be defined which will give equal test results regarding the above mentioned criteria as compared with the direct test circuit specified in IEC 127 for HBC miniature fuses. (1500A prospective current in a 250VAC circuit with $\cos\varphi \cong 0.8$) In trying to find an answer on this question we assume that pre-arcing conditions are comparable. This means that for one specific fuse type to be tested the $\int i^2 dt$ value and the instantaneous value of the current at the instant of fusing are equal in both test circuits.

2. THE ARC MODEL

For a theoretical approval of the above mentioned. question we start from the resistance - step - model for an arc in a fuse as developed earlier [3] [4] and which has proven to give an acceptable explanation of arcing behaviour in a fuse. Very briefly the resistance - step - model contains the following :

In case of short circuit the arc voltage coming into existance at the instant of fusing can be understood by the action of a resistance step with amplitude R_f at the instant of fusing t_1. The value of R_f is typical for a given fuse design and may also depend to some extend on the value of the current I_1 at the instant t_1. (see fig. 1) The self-inductance, present in any circuit in practice, opposes a sudden variation of current at the instant R_f arises, which means that at $t = t_1$ a voltage E_f across the fuse will arise, the value of which is determined by $E_f = I_1 R_f$. The power P_f at the instant $t = t_1$ is equal to $P_f = I_1 E_f = I_1{}^2 R_f$, which normally shows a maximal value at $t = t_1$. This means that the criterium for maximum arc power P_f includes a criterium for I_1, meaning that also conditions resulting from the pre-arcing period are taken into account.

In many cases in practice an increase of the arc-resistance during a certain period of time Δ will occur. Such an increase can be approximated by a linear increase during Δ, so R_f may show a time function as indicated in fig. 2. This will be the case as a consequence of multiple arcing and/ or burning back of the fuse element. The existance of a rise time Δ may lower the maximum value of the peak voltage to a value $e_{f\max} < E_f$. This is especially the case if the rise-time Δ is not very small compared with the time constant τ of the circuit from which the fuse forms a part.

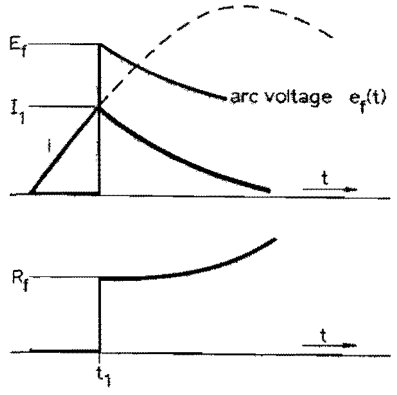

Fig. 1 : Arc voltage current and resistance wave forms of a fuse in case of short circuit.

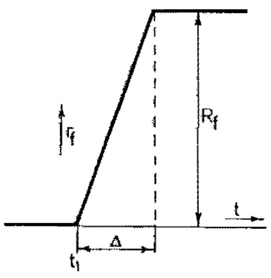

Fig. 2 : Arc resistance model

3. THE MAXIMUM ARC-POWER IN BOTH TESTING CIRCUITS

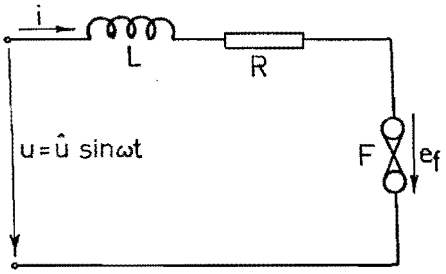

Fig. 3

Direct testing circuit

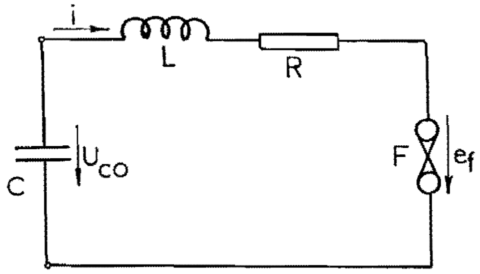

Fig. 4

Synthetic testing circuit

Fig. 3 shows, somewhat simplified, the direct testing circuit as specified in IEC 127 for the breaking capacity test for HBC-miniature fuses, whereas fig. 4 shows the synthetic test circuit using a capacitor as a current source.

A computer simulation has been made for the computation of the maximum arc voltage e_{fmax} in relation to the maximum possible arc voltage $E_f = I_1 R_f$ in both circuits, and using the arc model as shown in fig. 2.

For the circuit of fig. 3 the circuit parameters as derived from the IEC test circuit have been taken. The circuit parameters of fig. 4 have been chosen such that in both cases the pre-arcing conditions ($\int i^2\,dt$-value and the value of I_1) are equal.

Fig. 5 shows some computational results. In this graph e_{fmax} / E_f has been plotted as a function of Δ / τ_L, where τ_L is the circuit time constant in both circuits $\tau_L = L/R$. As a remark the capacitance in the synthetic circuit results in a time-constant $\tau_L = RC$ for which is valid $\tau_c >> \tau_L$.

From the graph of fig. 5 it can be seen that there is no big difference in values of e_{fmax} / E_f as a function of Δ / τ_L in both circuits. However, plotting e_{fmax}/E_f as a function of Δ and with relevant values of τ_L in both cases, a remarkable difference between the two circuits becomes visible. (see fig. 6) In the example of fig. 6, comparable results with respect to e_{fmax} are only possible using a charging voltage of the capacitor which is considerable lower than required, according to IEC 127.

As a remark, it has been shown in the past that good conformity exists between theoretical curves for the circuit of fig. 3, as shown in fig. 5, and experimental results [5]. Further, we remark that values of Δ at which a remarkable lowering of the peak arc voltage will occur, are quite normal values for miniature fuses at relevant values of short-circuit current to be interrupted.

So as a conclusion one may state that a difference between the peak arc voltage in both testing circuits is quite conceivable, meaning also that the maximum power P_f in both cases may differ remarkably from each other. Similar results with respect to P_f may be obtained if $\tau_L = L/R$ is equal in both testing circuits, but this condition will create a serious complication concerning equal pre-arcing conditions in both testing circuits.

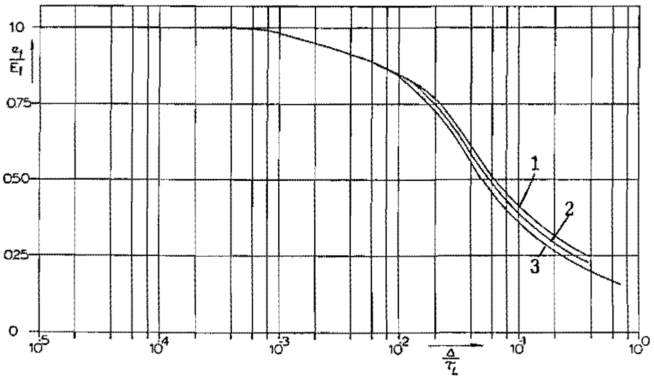

Fig. 5 : Lowering of the peak voltage as a function of $\frac{\Delta}{\tau_L}$.

1 : direct

2 : L = 420μH, E = 225V

3 : L = 230μH, E = 143V

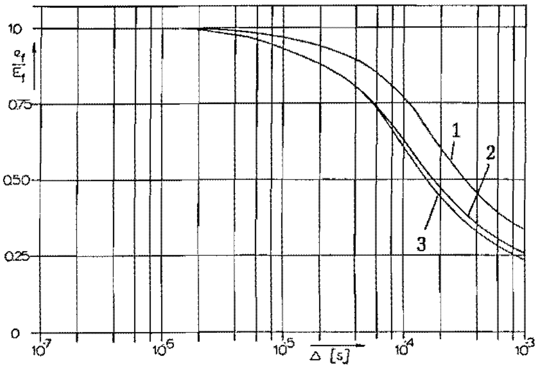

Fig. 6 : Lowering of the peak arc voltage as a function of Δ.

1 : $\hat{E} = 250\sqrt{2} = 353V$; $\tau_L = 4{,}44ms$

2 : direct, $\hat{E} = 250\sqrt{2}V$; $\tau_L = 2{,}63ms$

3 : $\hat{E} = 225V$; $\tau_L = 2{,}63ms$

4. THE ARC ENERGY IN BOTH TESTING CIRCUITS

In principle the behaviour of the arc in a fuse during the arcing period can be described by two simultaneous differential equations, viz :

- The energy balance equation of the arc in the fuse.
- The equation of the circuit from which the fuse is a part.

Solving both equations together may result in an expression for the arc energy in a given situation, providing that all physical and electrical parameters are known in sufficient detail. This leads to the conclusion that the arc energy is not only determined by the fuse parameters, but also greatly influenced by the parameters of the circuit from which it forms a part.

One can wonder if it is in principle possible to create in a totally different circuit equal conditions with respect to arc energy. This is the more so because a synthetic circuit (LRC-circuit), in contrary to the direct testing circuit, may show two different states (an aperiodic and a periodic state) which both may come into existance during testing of one fuse. It has been shown theoretically and proven experimentally [3] [6] that during fuse operation an LRC-circuit may be in the periodic state during the pre-arcing period, whereas during the arcing period the LRC-circuit may be in the aperiodic state. This will be the case if the fuse resistance R_f is larger than the critical resistance $R_c = 2\sqrt{\frac{L}{c}}$ of the circuit. So adjusting the LRC-circuit such as to create similar pre-arcing conditions does not garantee at all that during the arcing period also similar conditions occur.

This statement can be made more plausible by having a somewhat closer look at the differential equations describing the circuits of figures 3 and 4. For both circuits is valid :

$$u(t) = L\frac{di}{dt} + Ri + e_f(t)$$

Where $e_f(t)$ is determined by $e_f(t) = ir_f(t)$ and $r_f(t)$ is governed by the energy balance equation of the arc. For the arc-energy dW_b during the time interval dt is valid : $dW_b = e_f(t)i\,dt$, resulting in :

$$dW_b(t) = u(t)dt - Li(t)\frac{di}{dt} - Ri^2(t)dt$$

The voltage u(t) in fig. 3 is given by the expression :

$$u(t) = \hat{U}\sin(\omega t + \varphi)$$

whereas for fig. 4 is valid :

$$u(t) = \frac{1}{C}\int i(t)dt$$

which in general will result in different expressions for dW_b and, consequently, for $W_b = \int_{t_1}^{t_2} dW_b$ for both circuits.

It can be shown that in general for the circuit of fig. 3 the following is valid :

$$W_b = q_3\,\hat{U}\,\hat{I}$$

whereas for the circuit of fig. 4 we have :

$$W_b = q_4 \cdot U_{co}\,\hat{I}$$

where $\hat{I}$ and $\hat{U}$ are maximum values of current and voltage respectively and U_{co} is the charging voltage of the capacitor of fig. 4. The parameters q_3 and q_4 are rather complicated functions of circuit parameters, closing angle, $r_f(t)$, a.s.o. It is tempting to analyse these functions further, but the outcome is rather strong dependant on the amplied arc model for such an analysis, so the pratical value of such an analysis is questionable.

As a remark we like to mention that Boehne [7] already arrived at an expression for q_3, assuming that at $t = t_1$ a constant arc-voltage E_f comes into existance. To give somewhat more evidence of possible differences in arcing behaviour in both testing circuits, the current and voltage wave forms in both cases are shown schematically in figures 7 and 8, for the circuits of figures 3 and 4 respectively.

Fig. 8 shows the transition from the periodic state (for $t < t_1$) to the aperiodic state (for $t > t_1$), that means a transition from i_p to i_a in fig. 8. This will happen if for $t < t_1$ the resistance R is smaller than the critical resistance $R_c = 2\sqrt{\frac{L}{C}}$ of the circuit, whereas for $t > t_1$ is valid $R + R_f > R_c$. In pratical cases, the time constant $\tau = (R + R_f)C$ (assuming a constant fuse resistance R_f during the arcing period) which determines the rate of aperiodic discharge of the capacitor, is always far greater than the time constant $\tau_{f1} = L/(R+R_f)$ which determines the transient phenomena as indicated by the shaded area of fig. 8. In most pratical cases the initial fuse voltage $E_f = I_1R_f$ is much greater than the capacitor voltage U_{c1} at $t = t_1$. If this is so, it can be easily derived, introducing $R_f = nR_c (n > 1)$, :

$$I_a = \frac{U_1}{nR_c} << I_1$$

That means that the magnitude I_a of the aperiodic current (see fig. 8) is considerably less than the current I_1 at $t = t_1$. Further it means that the value of I_a and $i_a(t)$ depends on the voltage U_1 at the instant of fusing. Such a dependancy does not exist in the case of the circuit for direct testing as shown in fig. 3.

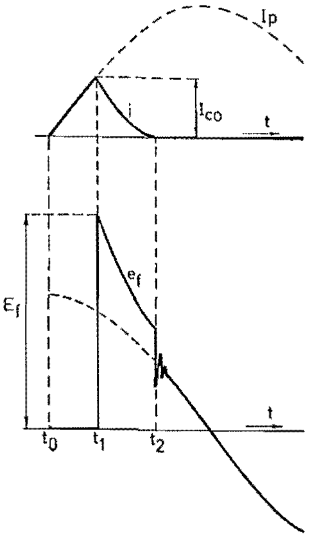

Fig. 7 : Current and voltage traces in a direct testing circuit.

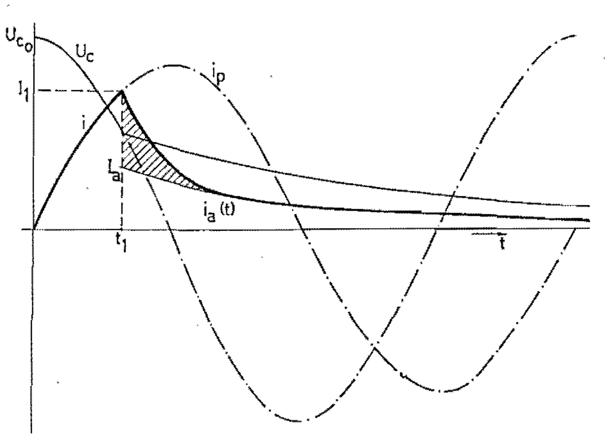

Fig. 8 : Current and voltage traces in a synthetic testing circuit.

5. CONCLUSIONS

In the preliminary some comparison has been made between the conditions for testing of miniature fuses in two different testing circuits. This comparison has been made, based on two criteria for the arcing period only, so it is assumed that equal test conditions occur with respect to the pre-arcing period. It is argued that equal conditions regarding the pre-arcing period in a direct testing circuit according to IEC 127 and a synthetic LRC testing circuit, does not necessarily mean that during the arcing period also equal conditions are present. Arguments are given for the statement that it is unlikely that both testing circuits will give comparable results with respect to the breaking capacity of fuses.

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