ELECTROTHERMAL RESPONSE OF FUSES ON INRUSH CURRENT OF DISTRIBUTION TRANSFORMERS

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Abstract: After presentation of today's approach to the h.v. fuse selection for protection of distribution transformers, the paper shows that more accurate selection can be made using detailed information on the transformer inrush current and the geometry and dimensions of the fuse-element. According to this approach the electrothermal response of the fuse-element on the inrush current should be calculated. As the examples, dry resin transformers of 100 kVA and 1000 kVA, 15/0.4 kV were tested in respect of their inrush current. Then the fuse-links selected according to existing rules were subjected to the inrush current. The existing thumb rule allows to select the same fuse rated current irrespective of the transformer type (e.g. dry resin or oil tank). Meanwhile the measured inrush currents for dry resin types are nearly 2 times lower then for the oil tank ones. Using the measurement results and simulations the paper comes to the conclusion that more realistic approach is when known inrush current has been taken into account in the computational checking procedure of the fuse-element thermal behaviour.

I. INTRODUCTION

Distribution transformers of the rated power up to ab 2 MVA are often protected by the h.v. fuses as a sole apparatus or as the back-up protection in a combination with the load switches. This technology is a well known practice since nearly of the beginning of the power electric supply. To avoid an undesirable fuse operation due to transformer inrush current the fuses rated current on the supply, i.e. h.v. side, shall be approximate to 2÷3 times of the transformer's rated current. In the last decades this rule was revised. It is now based upon a comparison of the t-I characteristic of the fuse and the transformer inrush current.

Irrespective of the fuse manufacturer the general rules of fuse selection are similar. A transformer imposes three main constraints on the fuse-link:

- It must withstand the current peak that accompanies switching on of the receiver without spurious melting.
- It must withstand the continuous service current and any permissible overloads.
- It must cut off defective currents on the transformer's secondary winding terminals.

Only the first constraint is under discussion in the paper. So the last two will be put aside of the scope.

The switching of the transformer is always accompanied by an inrush current the values of which depend on the moment of application of the voltage and the residual induction of the magnetic circuit (Fig.1).

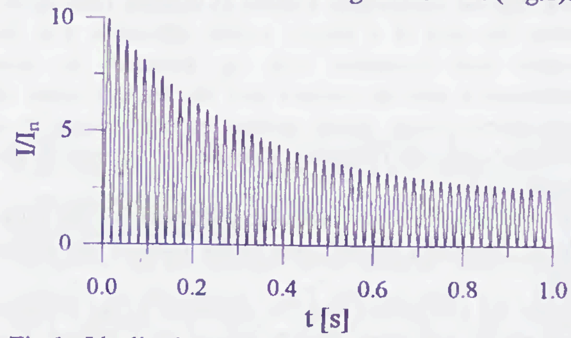

Fig.1. Idealised magnetising current of a power transformer. I_n – rated current of transformer

The current's asymmetry and value are at their maximum when energization occurs at zero voltage and when residual induction in the same phase is at a maximum.

For selection of the fuse-link the R.M.S. value and time of the inrush current must be known. It is shown that the R.M.S. value of the transient condition current is given by [1]:

$$I^2_{(RMS)} = 0.125 I^2_m \frac{\tau}{t}(1-e^{-\frac{2t}{\tau}}) \quad (1)$$

where: I_m – maximum peak current, τ – time constant of damping of current in seconds, t – time in seconds taken as $t=3\tau$ after which it is estimated that the current has reached its final value.

The I_m/I_n and τ depend upon rated power and type of a transformer. Usually larger the rated power lower this ratio and larger the time constant. E.g., France Standards UTE C.52-100, C.52-112 an C.52-113 give I_m/I_n from 15 to 8 and τ from 0.10 up to 0.45 s for the power range 50÷2000 kVA.

A simple and tested practical rule which takes this constraints into consideration and avoids ageing of the fuse-link repetition is to check that the current which melts the fuse in 0.1 s is always equal to or 10 or 12 (sometime even 14) times greater than the I_n current of the transformer. This rule sometimes is recommended by the fuse manufacturers irrespective of the type of transformer.

The rule has been in general use in many countries, and is, for example specified in the British Electricity Supply Industry (ESI) Specification 12-8. It is sometimes supplemented by the requirement that melting of the fuse-elements should not start in less than 10 ms when carrying 25 times the transformer rated current. The higher multiple (12 times) is used for fuse-links without strikers to provide sufficient margin to ensure that the fuse-links will not melt towards the end of magnetising-current surge.

When fuse-links with strikers which are arranged to trip associated switches being considered, it may than be permissible to accept the risk of a very occasional spurious fuse operation and so the lower multiple of ten times may be acceptable. Clearly if melting does occur toward the end of a surge, switch operation will be initiated and clearance will be effected. In this connection it will be realised that the highest value of magnetising-current inrush seldom occurs because it is associated with energization at particular instants in the voltage cycle.

It is clear that the time/current characteristic of the high-voltage fuse-links should pass to the right of the above points.

Despite the conviction that the approach to the problem given above has been already solved in a proper way since many years, still exist a need to make a closer look into it because:

- The electrothermal instantaneous response of a fuse-element on the inrush current can not be directly evaluated from simple rules mentioned above.
- The inrush current of modern dry resin transformers can be quantitative different than oil tank transformers.

That is why this closer look has been made using analytical simulation, but taking as the base the measured inrush currents of dry resin transformers 100 kVA and 1000 kVA.

II. ELECTROTHERMAL RESPONSE OF CONSTRICTED FUSE-ELEMENT ON INRUSH CURRENT

To make the simulations rooted in a concrete practice 100 kVA and 1000 kVA, 15/0.4 kV dry resin distribution transformers were tested in respect of their inrush currents using a point on wave (p.o.w.) 3-phase making-switch. Six different p.o.w. switching on were made within distance ab. 30 el. deg. between the consecutive shots. In both cases the maximum recorded I_m/I_n was ab. 10 times the transformer rated current (Fig.2). Recorded ratio is nearly 2 times smaller than applied now for fuse selection [2].

Also the time constants are smaller than being now in use. They are nearly 2 times smaller.

In the case of 100 kVA a fuse was chosen within notched Ag-strip fuse element, as it is shown in Fig. 3.

For simulations of the electrothermal response of that fuse-element on the inrush current given in Fig. 2 the

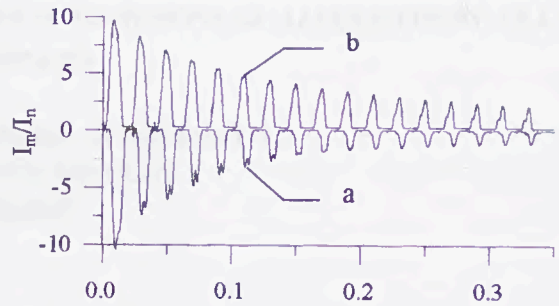

Fig.2. Inrush currents of 100 kVA and 1000 kVA, 15/0.4 kV, dry resin transformer with maximum I_m/I_n
a – 100 kVA, b – 1000 kVA

following simplifications were assumed:

a) The current density in given cross-section is constant.
b) The fuse-element number of notches is so large that the simulation can take into account only the section L in Fig.3.
c) The heat transferred to the sand is negligible. The thermal conductivity from notches into the fuse-element shoulders in a comparison into the sand is of order 10^3 greater. By taking this assumption one can avoid relatively vast computer numerical calculations being in use since the first publication on it [3]. Such a simplification introduces some error in the calculation results. For the pre-arcing times not greater than 0.1 s this error can be practically neglected.
d) The heat transfer perpendicular to the fuse-element plane is neglected for the obvious reasons.
e) The axial heat transfer to the fuse contacts is also neglected. The fuse-element for h.v. fuses is so long one that only fragments close to the contacts feel their presence.

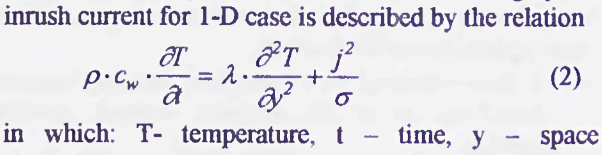

Fig.3. Fragment of fuse-element selected to protect 100 kVA transformer on 15 kV side

For above assumptions the fuse-element heating by the inrush current for 1-D case is described by the relation

$$\rho \cdot c_w \cdot \frac{\partial T}{\partial t} = \lambda \cdot \frac{\partial^2 T}{\partial y^2} + \frac{j^2}{\sigma} \qquad (2)$$

in which: T- temperature, t – time, y – space coordinate, ρ – mass density, c_w – specific heat, λ – thermal conductivity, j – current density, σ – electrical conductivity.

It has been assumed that the electrical conductivity between the initial temperature and the melting one is described by the relation

$$\sigma(T) = \frac{\sigma_0}{1+\alpha\cdot(T-T_0)} \tag{3}$$

in which: σ_0 – electrical conductivity at the initial temperature, α – thermal coefficient of electrical conductivity, T_0 – initial temperature.
The current density is defined by

$$j(y) = \frac{i}{S(y)} \tag{4}$$

in which: i – current, S – fuse-element cross-section.
The initial and boundary conditions for the fragment L (Fig.3) re given by

$$T\big|_{t=0} = T_0 \qquad \left.\frac{\partial T}{\partial y}\right|_{y=L} = 0 \qquad \left.\frac{\partial T}{\partial y}\right|_{y=0} = 0 \tag{5}$$

Using Crank-Nicholson scheme and MathCad package it was calculated temperature/time dependence in the notches up to the melting temperature. Reaching of the melting point means that the fuse-element is destroyed and that its rated t-I characteristic is not already assured. Results of calculations are demonstrated in Fig.4.

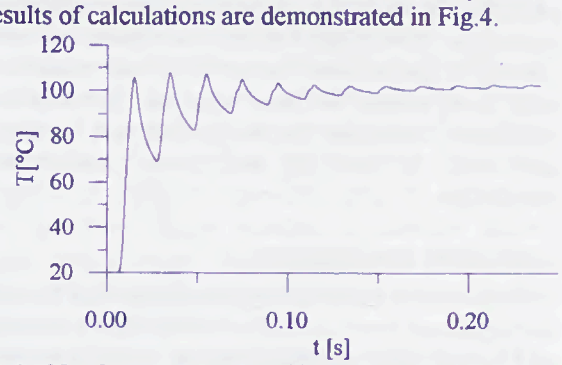

Fig.4. Notch temperature/time dependence for 100 kVA dry resin transformer

It is clear that the inrush current does not create any problem for the fuse-elements in question. The maximum temperature reaches only ab. 110°C. But if one takes into account that for oil tank transformers the I_m/I_n can reach even 24 (i.e. 2.4 of the tested dry resin transformers), the maximum expected temperature should be much higher. From this reason the temperature notches were recalculated, using the factor K of a value in the vicinity 2,2 (Fig.5).

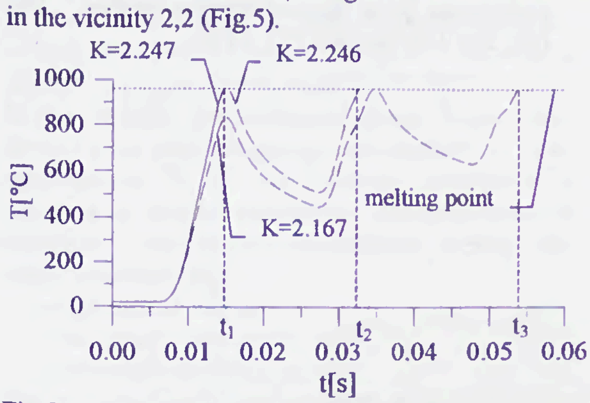

Fig.5. Temperature/time dependence for 100 kVA oil tank transformer recalculated from dependence in Fig.4 using factors K

It can be seen that a slight diminishing of K from 2.247 to 2.246 the fuse-element will start to melt at the instant t_2 instead t_1. But a bit greater diminishing of K down to 2.167 already gives the fuse-element melting in the instant t_3. So can arise a discontinuity of t-I characteristic similar to that described for semiconductor fuse-links [2]. The notch will reach melting point after 14.88 ms or 32.56 ms or even 53.64 ms by slight inrush current fluctuations.
Similar results one can get if the time constant will be longer than for oil tank transformers ones. To analyse this the time constant τ was changed according to the rule

$$K_1 = \frac{e^{-\frac{t}{\tau}} + a}{e^{-\frac{t}{\tau_0}} + a} \tag{6}$$

where: τ – recalculated time-constant, τ_0 – measured time-constant, for dry resin 100 kVA transformer, a – constant value read out from test record to which tends decaying inrush current.
Results of the calculations with enlarged time-constants indicate the possibility to get melting point after quite a long period of time (Fig.6). The fuse current interrupting ability of such small current can be dangerous, unless the fuse is not full-range one.

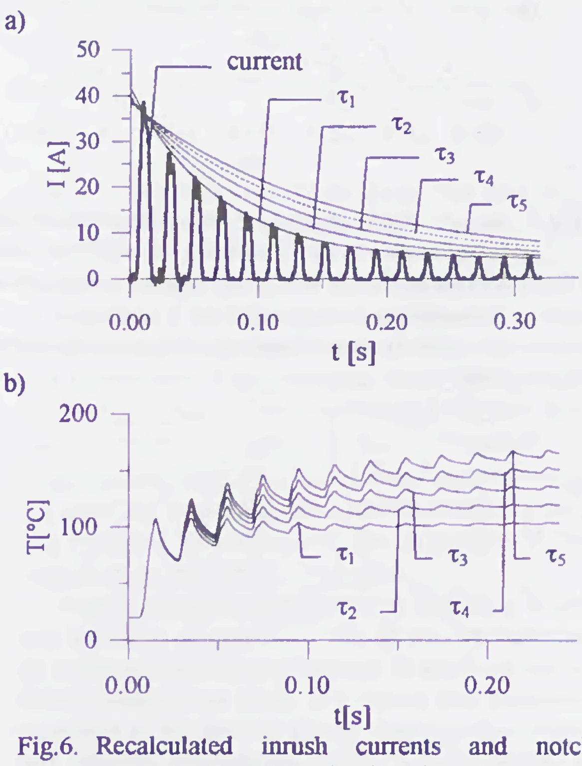

Fig.6. Recalculated inrush currents and notch temperature response in given inrush current
a - recalculated inrush current maxima envelopes versus time on the base on Fig.2 by use of constant K_1 (6);
b - recalculated temperature response for different K_1

Evaluation shows that the temperature values given in Figures 4, 5 and 6 up to 0.1 s only a few percents are higher than these but with taking into account the heat transfer into the sand.

It is necessary to underline that similar qualitative simulation results were obtained for 1000 kVA transformer and also for inrush current of a large asynchronous motor of rated power 309 kW, 3×380 V (Fig.7).

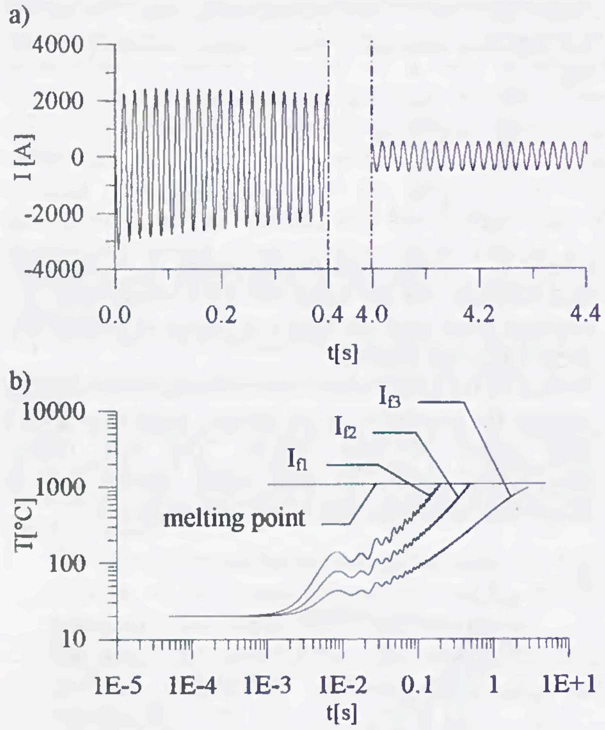

Fig.7. Motor start current and temperature/time dependence of l.v. fuse-links of different rated current $I_{f1}<I_{f2}<I_{f3}$ selected to protect motor circuit. Asynchronous motor 309 kW, 3 ×380 V.
a – current versus time, b – temperature versus time

III. CONCLUSION

The inrush current tests on distribution dry resin transformers of power 100 kVA and 1000 kVA, 15/0.4 kV show that its maximum value within 10 ms is ab. 2 times lower than that usually taken into account in the h.v. fuse-selection procedure. It is because the transformer design details are considerably different for dry resin and oil tank transformers.

Simplified simulations suggest that the fuse-elements subjected to the transformer inrush current during the first ten half cycles show analogous behaviour to the fuse-elements of fuses for semiconductor protection. There can appear discontinuity of the t-I characteristic.

In the case of long time-constants of the inrush current decaying it is possible the fuse arc ignition after some longer time which can lead to the spurious fuse operation.

The general conclusion is that being in use thumb rule, how to select h.v. fuses for the distribution transformers protection is far to be adequate to the electrothermal interaction between the fuse and the transformer inrush current. It seems, more correct h.v. fuse selection in such cases should be based upon the calculations of mentioned interaction. For the time being it is rather an easy task by use of the special computational programme.

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