Testing of High Breaking Capacity Fuses Using Modular Current Sources

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Abstract: - There are many types of switching and protection electrical apparatus used in different power systems with the goal to supply at adequate parameters industrial or domestic consumers. The time-current characteristics of the protection electrical apparatus from datasheets have accuracy up to ± 30%. Hence, in order to achieve a safe protection at overcurrents it is necessary to test the electrical apparatus using proper devices. Therefore, the aim of this paper is to present new types of modular current sources and some possibilities to adjust their parameters. Then, a method to obtain the time-current characteristics of low voltage high breaking capacity fuses without fusing is presented.

Key-Words: - modular current source, testing, method, high breaking capacity fuse

1 Introduction

The fuses testing are doing in concordance with some required conditions of norms and standards [1-5]. Some tests have a particular specificity and they are usefully both in research, production and even exploitation.

To get the time-current characteristics of fuses is one of the goals for specific overload tests. For this kind of test it uses different current sources which usually are fixed and belong especially to specialized industrial workshops, [6 - 10].

In the case of research testing or fuse exploitation (reconditioning), there is the necessity for adjustable and mobile modular current sources. On the other hand, the fuses time-current characteristics from datasheets of different manufactures actually are obtained from statistical computations and thus, in some practical situations these curves are not valid any more especially in the case of fuses reconditioning.

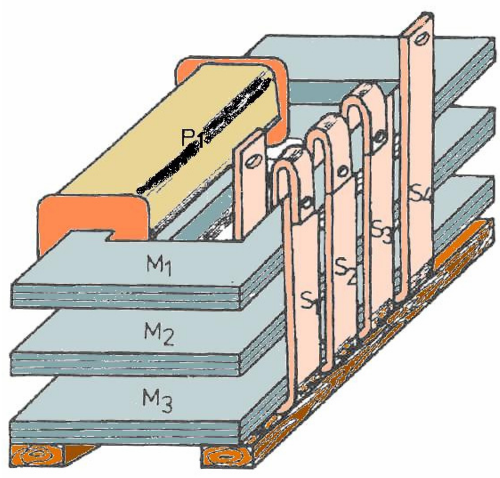
This paper describes the modular current sources [11 - 13], which can be used to test different type of fuses, especially high breaking capacity fuses, and also there are some contributions in order to plot time-current characteristics of fuses without fusing.

2 Modular Current Sources

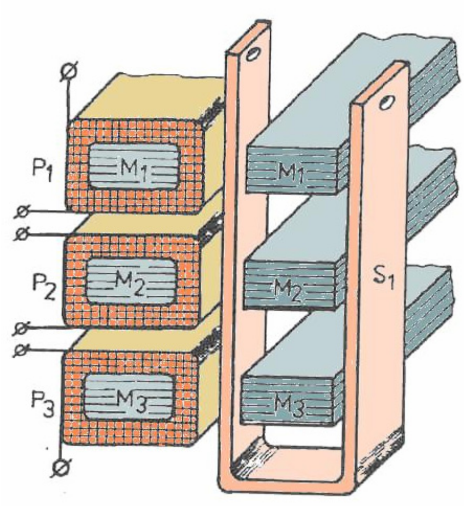
In order to have a wide range of adjustable currents and up to kA values, the current sources are built into a voltage – current transformer supplied with an autotransformer. These kind of current sources are not normally transportabled.

The modular electromagnetic source used in tests has a different number of ferromagnetic modules. One of the first constructive variant of the current source is shown in Fig.1. This kind of power current source includes a single-phase voltage-current transformer with independent ferromagnetic modules each one with its own primary winding and a common secondary.

During the time, the current sources have been built within many constructive versions taking into account the number of the adjusting steps, capability of being removed, easy to mount, minimum losses, etc. Further on, a brief summary is presented.



(a)



(b)

Fig. 1 Modular current source: (a) general view, (b) cross-section view; M_1, M_2, M_3 –modules; P_1, P_2, P_3 – primaries' windings; S_1, S_2, S_3 – secondaries

A. Horizontal mounting of the magnetic cores respect to the traditional construction

This is used to build current sources with three or more modules depending on the demand power, Fig.2. The advantages of these current sources mean an easy construction of the magnetic cores and a suitable mounting of the power assembly.

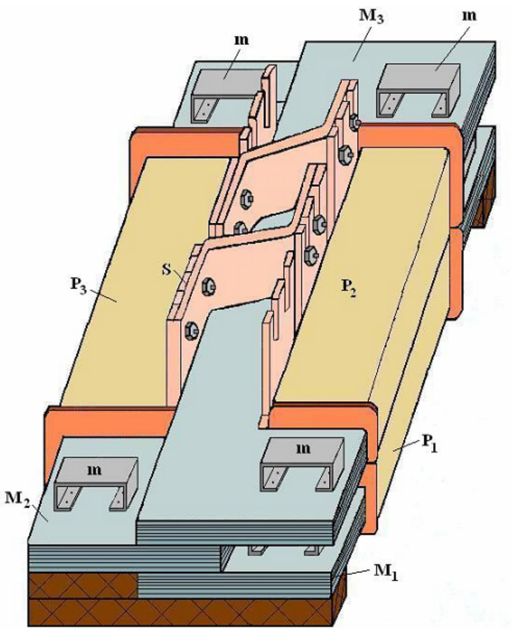


Fig. 2 Current source with horizontal mounting of the magnetic cores: M_1, M_2, M_3 – modules; P_1, P_2, P_3 – primaries; S – common secondary; m - handle

Also, the primaries' windings are separated and the secondary is not insulated which allow a thermal stress up to its thermal limit. The disadvantage means into a more difficult cooling of the primaries' windings on the bottom side of the power assembly and a complex general construction with many connections through the wires.

B. Vertical mounting of the magnetic cores within traditional construction

This solution means a better cooling of the windings, a symmetrical accessibility both to all primaries' windings and secondary, Fig.3. The construction allows using without any technological problems of different types of secondaries, from power cables of special construction to secondaries made from copper straps or solid bars.

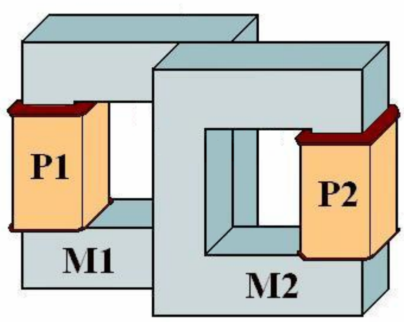
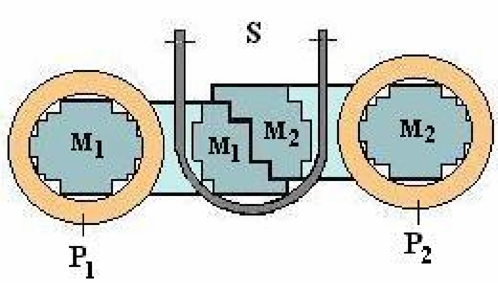


Fig. 3 Vertical mounting of the magnetic cores (P_1, P_2 – primaries; M_1, M_2 – magnetic cores)

C. Vertical mounting of the magnetic cores with column construction on which primaries' windings is placed

Both primaries and secondary have a circular construction. Thus, it obtains smaller impedance for secondary, a decreasing of the loss magnetic fluxes and a better cooling both for primaries and secondary. The constructive versions with two, three and four modules are shown in Fig.4…Fig.6.



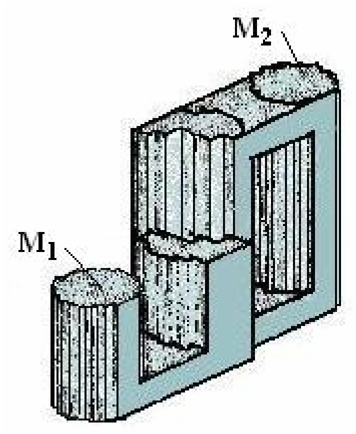


Fig.4 Current source with two vertical modules (P_1, P_2 – primaries; S – secondary; M_1, M_2 – magnetic cores)

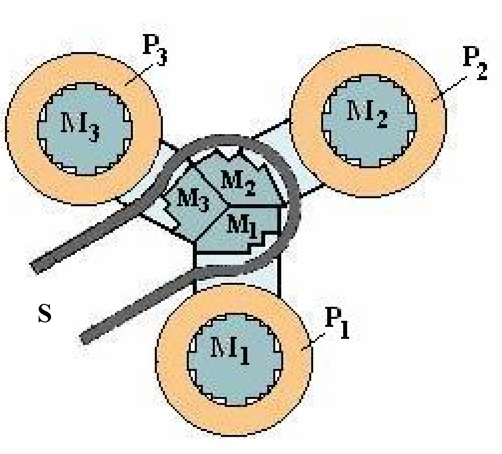
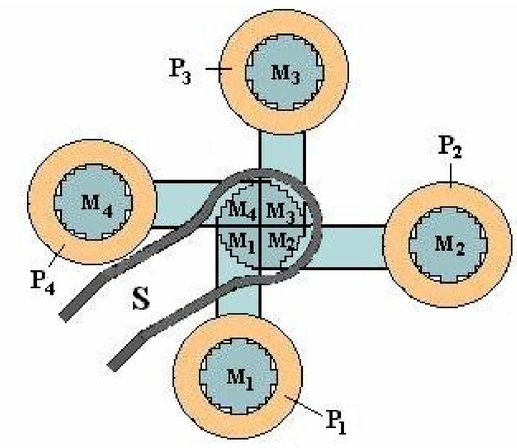


Fig.5 Current source with three vertical magnetic cores (P_1, P_2, P_3 – primaries; S – secondary; M_1, M_2, M_3 – magnetic cores)



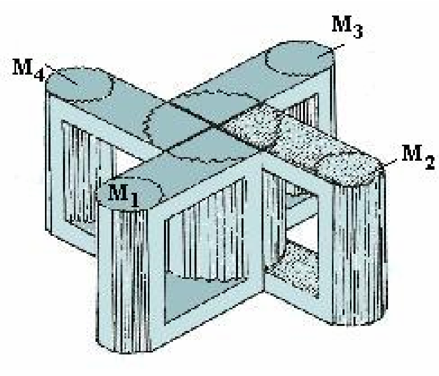


Fig. 6 Current source with four vertical magnetic cores (P_1, P_2, P_3, P_4 – primaries; S – secondary; M_1, M_2, M_3, M_4 – magnetic cores)

D. Vertical mounting of the magnetic cores with traditional construction or within steps

This solution depends on the demand power and on the magnetic cores' columns the primaries' windings are mounted. There is a common secondary which includes these columns, as shown in Fig.7.

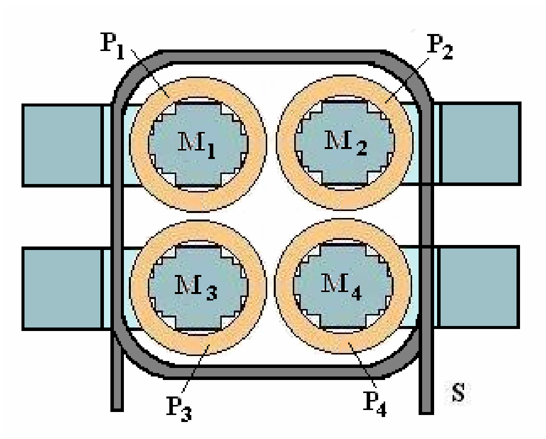


Fig. 7 Current source with vertical modules within traditional construction

3 Theoretical Aspects Related to Modular Current Sources

The following will make some considerations and analysis of functional equations of current designed sources and their equivalent diagrams, given the following assumptions:

- the iron magnetic core losses are considered very small, so they can be neglected;

- the magnetic cores are unsaturated, the operation taking place on the linear characteristic B (H) of

magnetic core;
- is considered modules have identical magnetic circuits;
- convention used in writing equations is from receiver for primary coils and from generator for secondary coils (common secondary).

Further on, it will present the mathematical equations of the modular current sources and the equivalent electric circuits. For a better understanding, it has been considered a current source made with only three ferromagnetic modules, as shown in Fig.8.

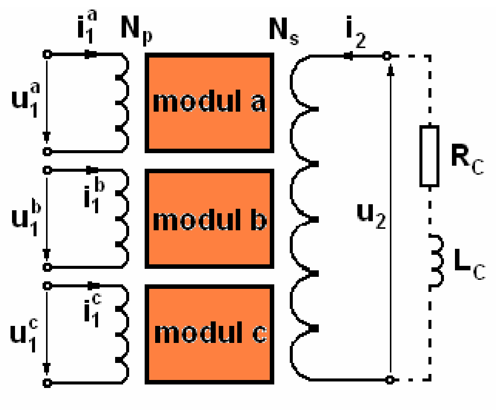


Fig.8 Block circuit of the current source with three ferromagnetic modules

All three modules are identically from constructive point of view, both magnetic and electrical:
- they have the same magnetic cores (sizes, materials, etc.);
- there is the same type of primary coils (the same number of turns N_p, made from the same material with identically sizes);
- there is a common secondary and has N_s turns.

The following general equations system can be written:

$$u_1^a = R_p\, i_1^a + L_{d12}^a \frac{di_1^a}{dt} + N_p \frac{d\Phi_0^a}{dt},$$

$$u_1^b = R_p\, i_1^b + L_{d12}^b \frac{di_1^b}{dt} + N_p \frac{d\Phi_0^b}{dt},$$

$$u_1^c = R_p\, i_1^c + L_{d12}^c \frac{di_1^c}{dt} + N_p \frac{d\Phi_0^c}{dt},$$

$$-u_2 = R_s\, i_2 + L_{d21}^a \frac{di_1^a}{dt} + L_{d21}^b \frac{di_1^b}{dt} + $$

$$+ L_{d21}^c \frac{di_1^c}{dt} + N_s \left(\frac{d\Phi_0^a}{dt} + \frac{d\Phi_0^b}{dt} + \frac{d\Phi_0^c}{dt} \right),$$

$$u_2 = R_c\, i_2 + L_c \frac{di_2}{dt} \quad ,$$

$$N_p\, i_1^a + N_s\, i_2 = N_p i_0^a,$$

$$N_p\, i_1^b + N_s\, i_2 = N_p\, i_0^b,$$

$$N_p\, i_1^c + N_s\, i_2 = N_p\, i_0^c, \qquad (1)$$

where:
u^a_1, u^b_1, u^c_1 mean the supply voltage for each primary;
i^a_1, i^b_1, i^c_1 – currents through each primary;
u_2, i_2 – the voltage on the secondary and its current;
$\Phi^a_0, \Phi^b_0, \Phi^c_0$ - the magnetic fluxes through magnetic cores;
i^a_0, i^b_0, i^c_0 – magnetization currents;
$L^a_{d12}, L^b_{d12}, L^c_{d12}, L^a_{d21}, L^b_{d21}, L^c_{d21}$ – dispersion inductances.

Considering $u^a_1 \neq u^b_1 \neq u^c_1$, involves $\Phi^a_0 \neq \Phi^b_0 \neq \Phi^c_0$ and $i^a_0 \neq i^b_0 \neq i^c_0$ with $i^a_1 \neq i^b_1 \neq i^c_1$. For sinusoidal quantities and non-saturated magnetic cores, the equations system (1) becomes:

$$\underline{U}_1^a = R_P\, \underline{I}_1^a + j\, X_{d12}^a\, \underline{I}_1^a - \underline{E}_{mp}^a;$$

$$\underline{U}_1^b = R_P\, \underline{I}_1^b + j\, X_{d12}^b\, \underline{I}_1^b - \underline{E}_{mp}^b;$$

$$\underline{U}_1^c = R_P\, \underline{I}_1^c + j\, X_{d12}^c\, \underline{I}_1^c - \underline{E}_{mp}^c;$$

$$-\underline{U}_2 = R_s\, \underline{I}_2 + j\left(X_{d12}^a + X_{d12}^b + X_{d12}^c\right)\underline{I}_2 - $$

$$-\left(\underline{E}_{ms}^a + \underline{E}_{ms}^b + \underline{E}_{ms}^c\right);$$

$$\underline{U}_2 = \underline{Z}_c\, \underline{I}_2 = R_c\, \underline{I}_2 + j\, X_c\, \underline{I}_2;$$

$$N_p\, \underline{I}_1^a + N_s\, \underline{I}_2 = N_p\, \underline{I}_0^a;$$

$$N_p\, \underline{I}_1^b + N_s\, \underline{I}_2 = N_p\, \underline{I}_0^b;$$

$$N_p\, \underline{I}_1^c + N_s\, \underline{I}_2 = N_p\, \underline{I}_0^c; \qquad (2)$$

with :

$$X_{d12}^i = w L_{d12}^i;$$

$$\underline{E}_{mp}^i = j\, N_P\, \underline{\Phi}_0^i;$$

$$\underline{E}_{ms}^i = j\, N_s\, \underline{\Phi}_0^i,$$

where *i* means the superscripts *a*, *b* and *c*.

The equivalent electric circuit is shown in Fig.9, and is made on the base of equivalent circuit type T of single-phase transformer. It obtains a 3T type diagram.

This kind of diagram can be used in order to study the possibilities of current adjustment on the secondary side and to model and simulate the transient and steady-state phenomena during current source operating.

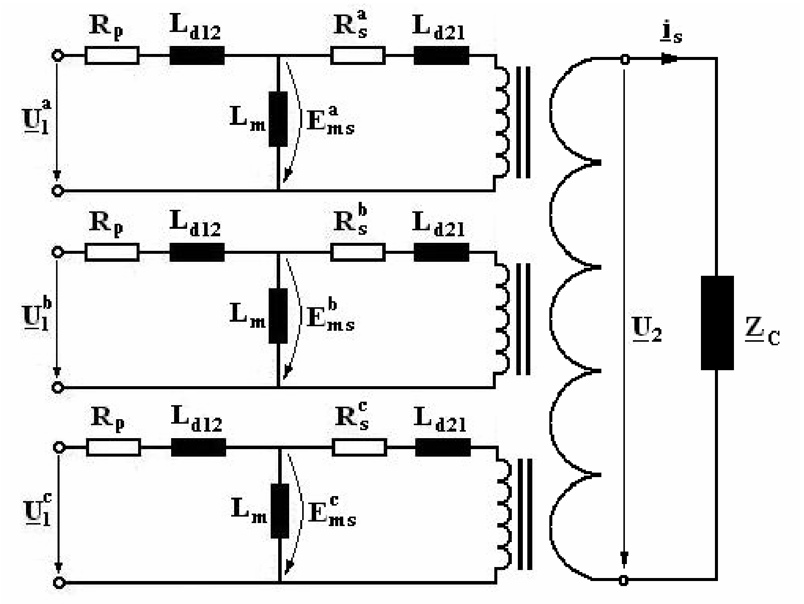


Fig. 9 The equivalent electric circuit of current source with three modules

4 Adjusting of the Secondary Quantities

It will take into account the following assumptions:

- there are only three modules, identically from electrical and magnetic point of view;
- the magnetic cores' operating are not in the saturation zone;
- there are steady-state conditions with sinusoidal waveforms.

Analogous to other type of supply sources, the adjusting of the quantities can be made in two ways, [14 - 16]:

a. step adjusting
- connecting the primaries' windings in series and/or parallel way;
- changing the number of the active modules (with supplied primaries), respect to the number of the passive modules (with short-circuited primaries' windings)
- changing the turns' number form the secondary.

b. continuous adjusting
- changing the voltage supply of the primary for one modulus and the others being in active state (supplied with maximum admissible voltage) or passive state;
- changing the value of the impedance mounted on the primary;
- changing continuously the supply voltage of all primaries connected in series or parallel;
- including in the secondary circuit of variable impedance.

Further on, it will analyse only the case specific to power current source: the step adjusting through the changing of the active modules number and continuous adjusting through variable voltage supply from zero to maximum admissible value for only one primary. The electric circuit is presented in Fig.10.

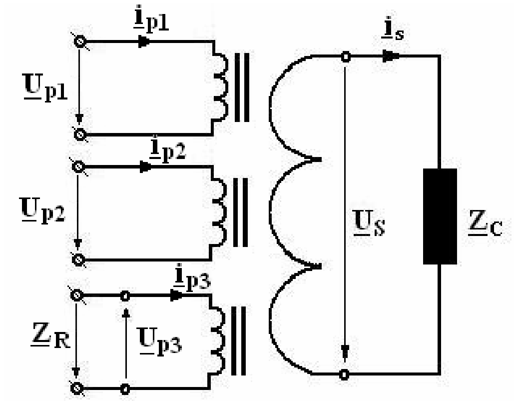


Fig. 10 The power circuit to analyse the adjusting of the quantities

The equations' system (2), in this case become:

$$\underline{U}_{p1} = R_P\,\underline{I}_{p1} + j\,X_{d1s}\,\underline{I}_{p1} - \underline{E}_{mp1};$$

$$\underline{U}_{p2} = R_P\,\underline{I}_{p2} + j\,X_{d2s}\,\underline{I}_{p2} - \underline{E}_{mp2}$$

$$-\underline{U}_{p3} = R_P\,\underline{I}_{p3} + j\,X_{d3s}\,\underline{I}_{p3} - \underline{E}_{mp3}$$

$$
\begin{aligned}
&-\underline{U}_s = R_s\,\underline{I}_s + j\left(X_{ds1} + X_{ds2} + X_{ds3}\right)\underline{I}_s - \underline{E}_{ms};\\
&N_p\,\underline{I}_{p1} + N_s\,\underline{I}_s = N_p\,\underline{I}_{0p1};\\
&N_p\,\underline{I}_{p2} + N_s\,\underline{I}_s = N_p\,\underline{I}_{0p2};\\
&N_p\,\underline{I}_{p3} + N_s\,\underline{I}_s = N_p\,\underline{I}_{0p3};\\
&\underline{U}_s = \underline{Z}_c\,\underline{I}_s\ ;\ \underline{U}_{p3} = \underline{Z}_R\,\underline{I}_{p3}.
\end{aligned} \tag{3}
$$

The voltage U_s in the case when the secondary has no load, will gets the following expression,

$$
\begin{aligned}
&U_s = E_{ms} = E_{1ms} \pm E_{2ms} =\\
&-N_s\frac{d\Phi_{mp1}}{dt} \mp N_s\frac{d}{dt}\left(\Phi_{mp1} \pm \Phi_{mp2}\right) =\\
&-N_s\frac{d}{dt}\Phi_r
\end{aligned} \quad . \tag{4}
$$

It observes that the secondary voltage values depend on the way how the electromotive forces from secondary because of the fluxes Φ_{mp1} , Φ_{mp2}, will sum. Hence, the resulted electromotive force variation ca is obtained in two ways:

a. at the beginning the flux $\Phi_{mp2} = 0$, and the flux Φ_{mp1} varies continuously from zero to maximum admissible value; then the flux Φ_{mp1} is maintained at a constant value and the flux Φ_{mp2} will vary from zero to maximum admissible value. It has to pay the attention that these fluxes should sum each other.
b. it maintains the electromotive force E_{ms} equal to zero because of two differential fluxes that the electromotive forces because of these fluxes should subtract. Then, one of the flux decreases up to zero value when the secondary electromotive force will increase from zero to maximum value according to the other flux. Then, it will invert the direction of the first flux through an adequate supply of the primary winding, with the aim to obtain both fluxes in the same direction. Hence, when the first flux will increase up to the maximum value it will obtain the maximum value of the electromotive force from the secondary.

With the aim to obtain the secondary current expression it takes into account the following assumptions:

- it states the quantities of the primaries' windings to the common secondary (it will notes with ");
- the magnetization currents are a negligible quantity:

  $I''_{pi} + I_s \approx 0$, where i = 1...3;
- the modules' position is symmetrically in order to get the same dispersions.

From the equations' system (3), it obtains the expression:

$$
\underline{I}_s = \frac{\underline{U}''_{p1} + \underline{U}''_{p2}}{3\underline{Z}''_p + \underline{Z}''_R + \underline{Z}_c + \underline{Z}_S} \tag{5}
$$

where:

$\underline{U}''_{p1} = \frac{N_2}{N_1}\underline{U}_{p1}$, $\underline{U}''_{p2} = \frac{N_2}{N_1}\underline{U}_{p2}$,

$\underline{Z}''_p = R_p + jX_{dp}$, X_{dp} means the primary-secondary dispersion reactance for one modulus;

$\underline{Z}''_R = \underline{Z}_R\left(\frac{N_2}{N_1}\right)^2$, reported adjustment inductance;

$\underline{Z}_c = R_c + j\,X_c$, load inductance;

$\underline{Z}_s = R_s + 3\,j\,X_{ds}$,

X_{ds} secondary-primary dispersion reactance for one modulus.

From the above expression results that the secondary current values depend on the following quantities:

- primaries' voltage supply;
- values of the adjustment impedance Z_R;
- values of the ratio from primaries and secondary turns;
- values of the dispersion inductances;
- values of the load;
- the quality of the magnetic material.

A general expression, (6) can be obtained for (n) modules where (m) modules have connected on the primary side the adjustment impedances $\underline{Z}''_{Rk}$ (where k = l...m), and (n-m) modules are supplied with the voltages $\underline{U}''_{pi}$ (where i = l...n-m).

$$
\underline{I}_s = \frac{\sum_{1}^{n-m} U''_{pi}}{\sum_{1}^{n} Z''_{pj} + \sum_{1}^{m} Z''_{Rk} + \underline{Z}_c + \underline{Z}_S} \tag{6}
$$

where:

$\underline{Z}_S = R_S + n\,j\,X_{dS}$

5 Time-Current Plotting Method

Nowadays time-current characteristics shown in datasheets and standards are curves of statistical mean values experimentally established. In the individual cases the deviations could be up to ± 30% from average values, an unacceptable error, especially to the protection of installations with power semiconductors. Thus, it is necessary to work out a method to establish the individually time-current characteristic of high breaking capacity fuses.

It has been tested high breaking capacity fuses fitted out with an iron-constant thermocouple with small thermal inertness and sticked to fuselink with a tin alloy (melting point, θ_{top} = 216°C). As a result, it could measure the temperature values at different currents and it has been obtained the curve from Fig.11.

The limit temperature what can be obtained without fusing, was considered $\theta_{lim} = 0.9\theta_{top}$. The θ(I) curve can be approximated with a parabolic function:

$$\theta(I) = K_{med} I^2 \tag{7}$$

where K_{med} is a constant (average value) obtained from experimental data.

A better approximation for θ(I) curve is obtained with the expression [17, 18]:

$$\theta(I) = Ash\left(a\frac{I}{I_n}\right) \tag{8}$$

where **A** and **a** are constants what can be calculated from experimental data.

The θ(I) curve, from extrapolation, using one of expressions before, can be known over θ_{lim}. For value of currents $I_1, I_2 \ldots I_m$ from the range I_{mintop} - I_r (minimum melting current - breaking capacity) using curve from Fig.11, it can establish the maximum heatings $\theta_{max1}, \theta_{max2} \ldots \theta_{maxm}$.

Then, it plots the heating curve θ(t) for values of currents $I_1, I_2 \ldots I_m$, Fig.12. In the range θ_{lim} - θ_{top}, the heating curve can be approximated with an exponential curve. The maximum heatings θ_{max1}, $\theta_{max2} \ldots \theta_{maxm}$, result from diagram before, Fig.11.

In the crossing points of heating curves θ(t) with the line $\theta = \theta_{lim}$ (points A, B...) it plots the tangents to those curves, getting the time thermal constants T_1, $T_2 \ldots T_m$. These constants can be obtained analytically with the relation:

$$T_i = \frac{t_i}{\ln\left(\frac{\theta_{\max i}}{\theta_{top} - \theta_{\lim}}\right)}, \quad i = \overline{1,m} \tag{9}$$

There is a critical current value, I_{cr} where the heating evolution is the line:

$$\theta(t) = ct \tag{10}$$

where **c** is a constant what can be calculated using the fuse parameters. Over that current value I_{cr}, the prearcing time has the expression:

$$t_{pa} = \frac{S^2 K}{I^2} \tag{11}$$

where K is a material constant and S is the cross section of fuselink.

Knowing these elements and material constants, it proposes the next methodology to establish the individually time-current characteristic without fusing:

- for some values of currents $I_1, I_2 \ldots I_m$ from the range I_{mintop} - I_r, it establishes the maximum heatings $\theta_{max1}, \theta_{max2} \ldots \theta_{maxm}$ using a curve like that shown in Fig.11;
- it gets the times $t_1, t_2 \ldots t_m$, resulted from crossing of heating curves θ(t) with limit temperature line $\theta = \theta_{lim}$, Fig.12;
- plotting the tangents in the crossing points established before, it gets time thermal constants T_1, $T_2 \ldots T_m$ or using the relation (9);
- it calculates the prearcing times: $t_{p1} = t_1 + T_1$, $t_{p2} = t_2 + T_2 \ldots t_{pm} = t_m + T_m$.

If currents are over the critical value I_{cr}, the prearcing times calculate with relation (11).

- the time-current characteristic t(I), meaning the operating time variation of one fuse depending on overcurrent, can express in two ways: melting characteristic $t_{pa}(I)$ and interrupting characteristic τ(I).

Because the arcing time of electric arc is about 5 ms, in the overcurrent area the characteristics $t_{pa}(I)$ and τ(I) actually overlap, Fig.13.

To validate the method some experimental tests have been done A diagram with the electric circuit used for experimental tests is shown in Fig. 14. The switch K, allow supplying with low-voltage the auto-transformer ATR, which adjusts the input voltage for the current supply CS. The main current from CS, flows through the fuse F, and will warm it. The current value is measured by an ammeter A, through a current transformer CT. Using proper thermocouples Th, it has measured the temperature of the fuselinks. The voltage signals from thermocouples have been acquired and processed by a data acquisition board and a PC.

It has been tested a series of gG type fuses with the following rated currents: 32, 63 and 100A. The resulted characteristics are presented in Fig.15.

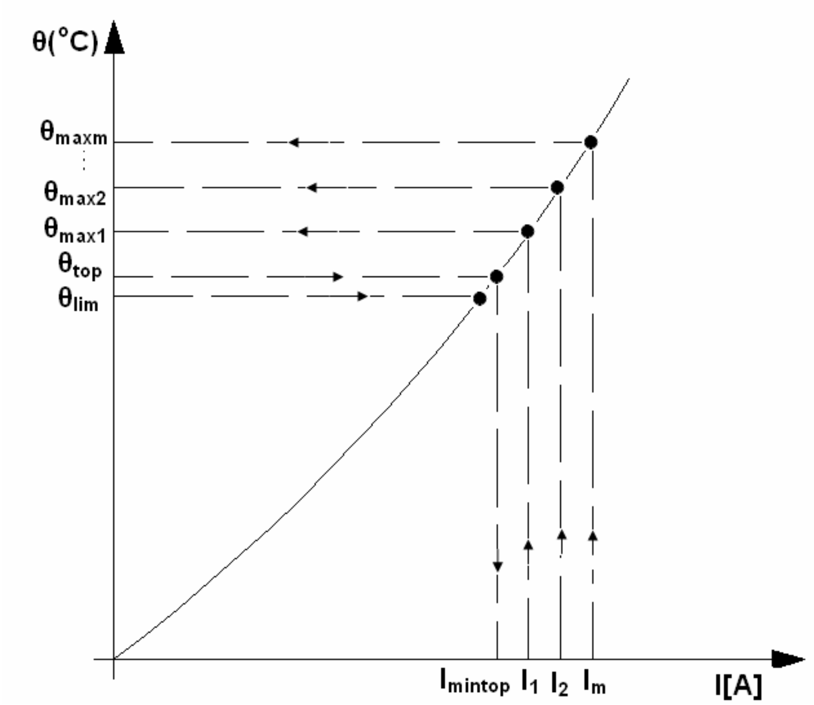


Fig.11 Temperature vs. current

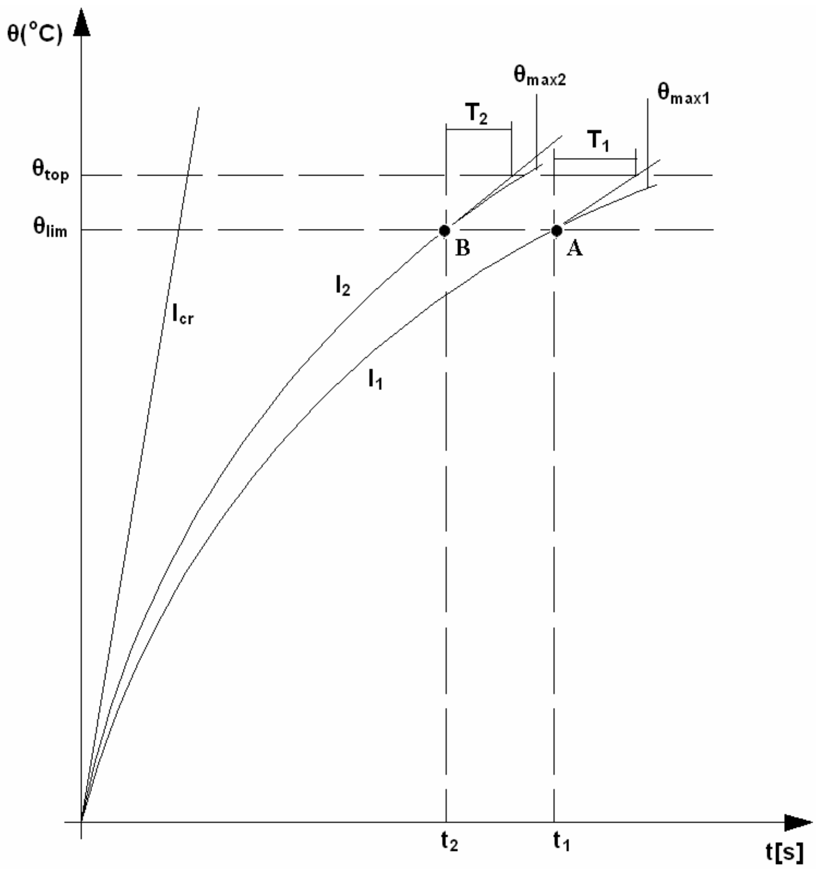


Fig.12 The heating curve

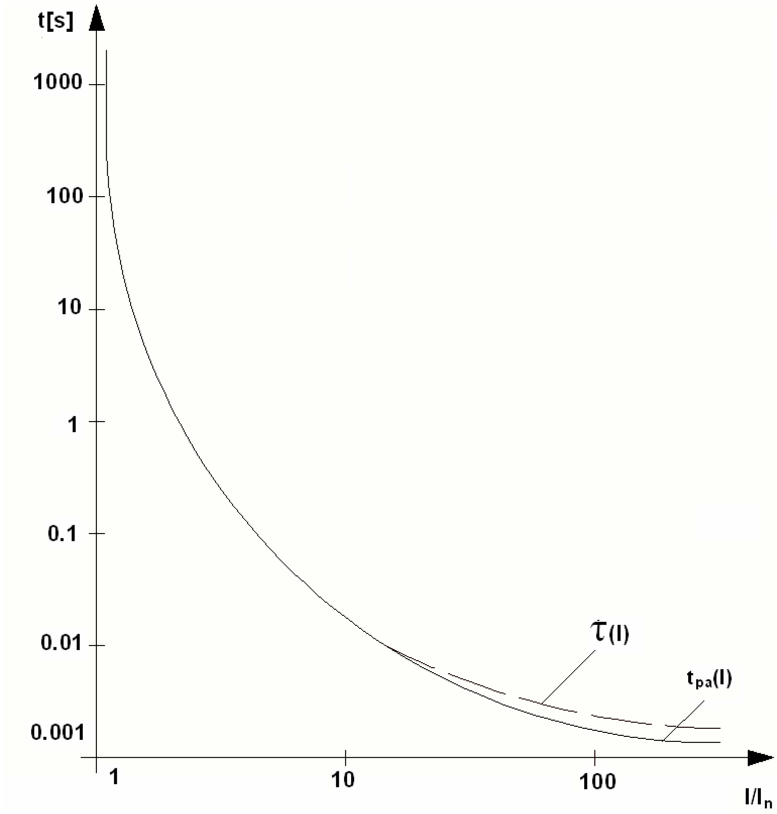


Fig.13 Time-current characteristic

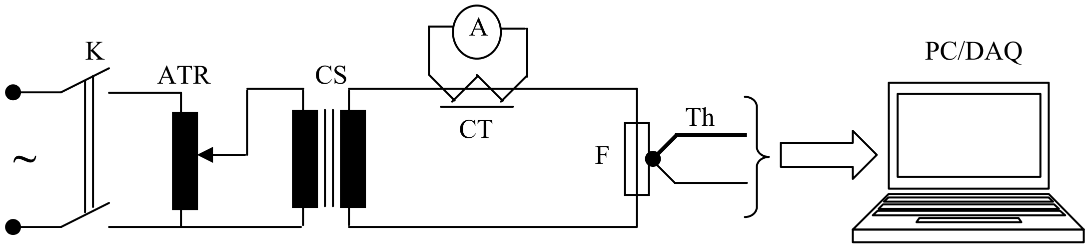


Fig.14 Experimental tests set up

It observes that for every type of tested fuse there is a range where the time-current characteristics can be plotted. This is explained because of technological mounting dispersion and previous thermal state.

6 Conclusion

From all experimental tests and theoretical aspects, the following conclusions may be outlined:

- there is the possibility to plot the time-current characteristic, t(I) of high breaking capacity fuses without fusing;
- knowing the time-current characteristic of high breaking capacity fuses, allow a correct protection and anticipated checking of electric installations protection;
- the selectivity between series fuses may be checked and can be safety set up;
- the quality of overcurrent protection at different industrial electrical installations increases;
- there is the possibility for a better protection of electric devices in the area of overload currents, using replacement elements of fuselinks with prescribed melting temperature.

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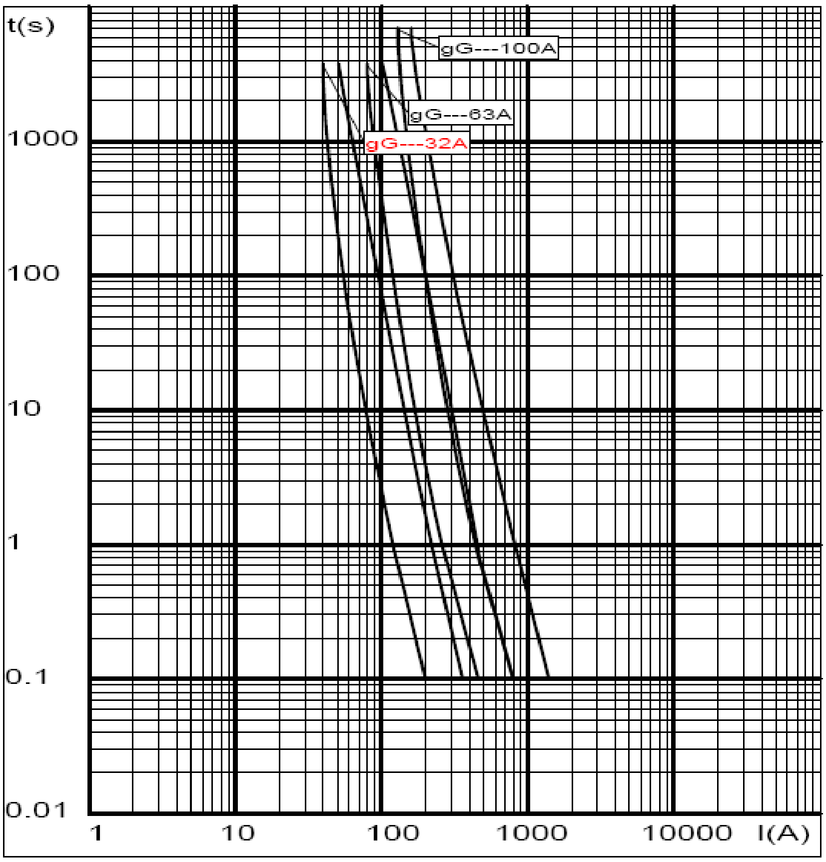

Fig.15 The time-current characteristics for the tested fuses

References:

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