

MODELLING OF METAL OXIDE SURGE ARRESTERS AS ELEMENTS OF OVERVOLTAGE PROTECTION SYSTEMS

SUMMARY

Metal oxide surge arresters are used for protection of high and low voltage electric devices against overvoltages. Mathematical models of surge arresters should properly represent current-voltage dependencies of varistors during influence overvoltages. From among numerous models created so far two versions of a selected model were used for computer simulations of current-voltage dependences of surge arresters. Parameters of elements of the selected model can be calculated by use of data published in the catalogues. Current-voltage dependencies of the surge arrester designed for electric power systems of 110 kV for different current stroke were modelled. The results of computer simulations were compared with the experimental data.

Keywords: surge arresters, mathematical modelling

MODELOWANIE OGRANICZNIKÓW PRZEPIĘĆ Z TLENKÓW METALI JAKO ELEMENTÓW SYSTEMÓW OCHRONY PRZEPIĘCIOWEJ

Ograniczniki przepięć są powszechnie stosowane do ochrony przepięciowej urządzeń elektrycznych wysokiego i niskiego napięcia. Modele matematyczne ograniczników powinny właściwie odzwierciedlać charakterystyki napięciowo-prądowe warystorów podczas oddziaływania przepięć. Spośród wielu modeli opracowanych dotychczas do symulacji komputerowych zależności napięciowo-prądowych wybrano jeden model ograniczników. Parametry elementów modelu wyznaczono przy wykorzystaniu danych katalogowych. Modelowano zależności napięciowo-prądowe dla różnych udarów prądowych ogranicznika przepięć stosowanego w układach elektroenergetycznych 110 kV. Obliczenia porównano z wynikami badań.

Słowa kluczowe: ograniczniki przepięć, symulacje komputerowe

1. INTRODUCTION

Metal oxide surge arresters are fundamental elements of protecting systems of electric devices against overvoltages. They contain varistores, which main constituent is zinc oxide as well as small amounts of other metal oxides. Surge arresters are exposed to transient effect of overvoltages generated as a result of lightning discharges, switching and damage states in electric power systems.

Modelling of surge arresters being in transient states, in case of large currents' flow accompanying overvoltages has a practical importance. Analysing the risks of electric insulation systems of protected devices while overvoltages are exerting their influence, it is essential to know the voltages of arresters. The voltages determine efficiency of overvoltage protection of devices. Theoretically, voltage-current dependencies in established operation conditions make it possible to determinate energy dissipated in arresters, as well as taking into consideration influence of the arrester on currents in the circuit into which is it connected.

Full and simplified version of a model of metal oxide surge arresters, selected from numerous types of models are presented in the paper. Parameters of the elements can be determined on the basis of investigation carried out by producers as well as taking basic dimensions into consideration. Current-voltage dependencies of the surge arrester designed to 110 kV electric power systems were simulated. The results of calculations were compared to the experiment data.

2. MECHANISM OF CURRENT CONDUCTIVITY IN METAL OXIDE VARISTORES

Surge arresters contain one or more varistores with various diameters and heights. Varistores are made of ceramic of non-linear voltage-current characteristic. It is a ceramic of zinc oxide with admixtures of other metal oxides – i.e. of bismuth, cobalt, manganese and aluminium. Structure of the varistores' mass is in the shape of close-packed grains. A small part of the grains constitute admixtures inside the grains while others, mainly bismuth, are accumulated in outer layers. Resistivity of the grain inside are small as opposed to resistivity of outer layers. Non-linearity of the voltage-current characteristic results from phenomena occurring just mainly on the boundary of the grains. Between grains appear potential barriers, which regulate intensities of currents in dependence on voltage, as on the grain boundaries is considerable negative charge accumulated, being a result of existence of acceptor admixtures. With small voltage, voltage-current characteristic remains in accordance with the Ohm's law, and depends on temperature. While increasing the voltage, energies of electrons can be high enough to pull electrons out of valence band. Electron-hole pairs of charges are created. Holes direct towards negatively charged boundary between grains, neutralising considerably surface charge and contributing to decrease of potential barrier. Sudden decrease of this barrier results in rapid current increase in the varistor. In this work range is the characteristic strongly non-linear. The non-linearity decreases, however, with po-

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tent lightning currents flow. With high density of currents, voltage increase is revealed, as a result of rise of voltage drop on grain-inside resistance. Character of phenomena on the grain boundary is the same as with lower current density. Dynamic properties of charges on inter-grain boundaries influence voltage-current dependencies. With very steep impulses, voltages on varistors increase faster than currents. Their maximal values are also higher for currents with shorter duration. These dependencies result from inertia of charge translocating in form of holes towards boundaries, decreasing barrier of potentials [1–3].

3. CHARACTERISTIC OF SELECTED MODEL OF SURGE ARRESTERS

Research aiming to create a mathematical model of metal oxide surge arresters, which enables modelling of current-voltage relations in any work conditions, have been carried out for many years. Numerous models are the result of research carried out hitherto. They are presented, among others, in the references [4–13]. To calculations was used this model of which parameters can be calculated using the experimental values of residual voltages presented in manufacture catalogues and basic dimensions of surge arresters. The model has been worked out by the IEEE Working Group 3.4.11 (The Institute of Electrical and Electronic Engineering) to calculate voltage-current dependencies in case of impulse currents flow with times of accretion of wave front from 0.5 μs to 45 μs (Fig. 1) [11, 12]. It contains two non-linear resistors $A_0(i)$ and $A_1(i)$ with various voltage-current characteristics, separated by a L_1 - R_1 filter. A capacitor C represents capacitance of the arrester. To improve stability of calculations, a resistor R_0 is connected parallel to the inductance L_0 . Parameters of linear elements and characteristics of non-linear resistors of the schema can be determinate from results of investigations of arresters, published in catalogues, as well as from elementary dimensions of the column of varistors.

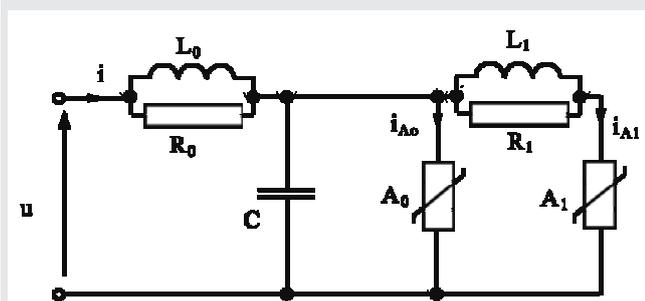


Fig. 1. Model of surge arresters worked out by IEEE

Characteristics of varistors A_0 and A_1 of surge arresters with rated discharge current I_r are represented by formulas:

$$A_0 = A_{w_0} \frac{U_{8/20; I_r}}{1.6} \quad (1)$$

$$A_1 = A_{w_1} \frac{U_{8/20; I_r}}{1.6} \quad (2)$$

where:

$U_{8/20; I_r}$ – residual voltage with rated current impulse I_r of times 8/20 μs,

A_{w_0}, A_{w_1} – dependencies approximated by use of formulas,

$$A_{w_0} = c_0 i_{A_0}^{0,051} \quad (3)$$

$$A_{w_1} = c_1 i_{A_1}^{0,0507} \quad (4)$$

where:

i_{A_0}, i_{A_1} – densities of currents in varistors A_0 and A_1 ,

c_0, c_1 – constants ($c_0 = 1.378, c_1 = 1.083$).

Parameters of linear elements L_0, R_0, L_1, R_1 and C are expressed by dependencies:

$$L_0 = 0.2 \frac{d}{n} \quad [\mu\text{H}] \quad (5)$$

$$R_0 = 100 \frac{d}{n} \quad [\Omega] \quad (6)$$

$$L_1 = 15 \frac{d}{n} \quad [\mu\text{H}] \quad (7)$$

$$R_1 = 65 \frac{d}{n} \quad [\Omega] \quad (8)$$

$$C = 100 \frac{n}{d} \quad [\text{pF}] \quad (9)$$

where:

d – height of the column of varistors, m,

n – number of parallel varistor columns [11].

As it appears from dependencies (1)–(9) the basis to calculating the parameters of elements of the model are results of studies of decreased voltage, presented in firm catalogues as well as main dimensions of the column of varistors. Correcting values of constants c_0, c_1 and inductance L_1 can augment accuracy of calculations (Fig. 2).

In calculations is this value taken, with which are the results of calculations converge with results of studies published in catalogues. The current-voltage equations for model of surge arresters presented in Figure 1 have the following form:

$$i(t) - C \frac{du_{A_0}(t)}{dt} - i_{A_0}(t) - i_{A_1}(t) = 0 \quad (10)$$

$$\frac{du(t)}{dt} - \frac{du_{A_0}(t)}{dt} - R_0 \frac{di(t)}{dt} - \frac{R_0}{L_0} [u(t) - u_{A_1}(t)] = 0 \quad (11)$$

$$\frac{du_{A_0}(t)}{dt} - \frac{du_{A_1}(t)}{dt} - R_1 \frac{di_{A_1}(t)}{dt} + \frac{R_1}{L_1} [u_{A_0}(t) - u_{A_1}(t)] = 0 \quad (12)$$

Systems (10)–(12) comprise non-linear equations.

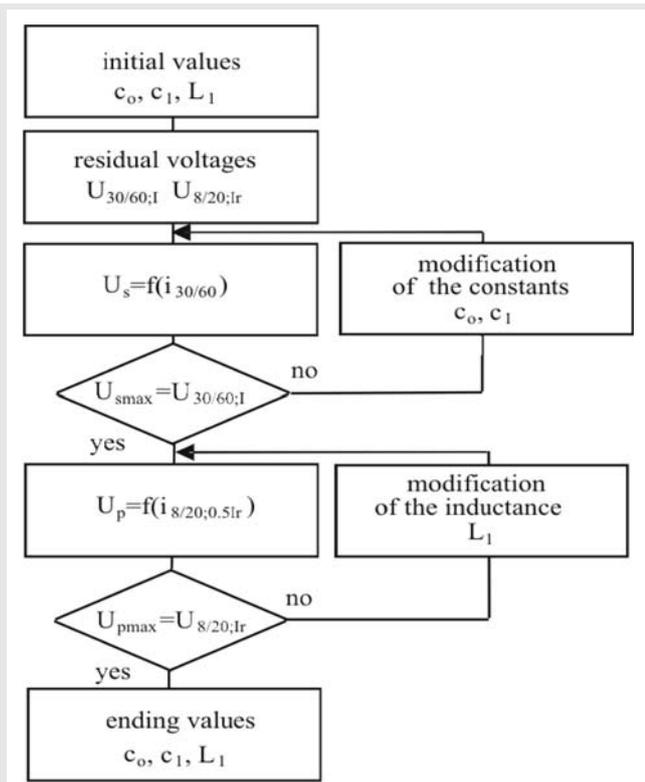


Fig. 2. The block scheme of the correcting process of the model parameters

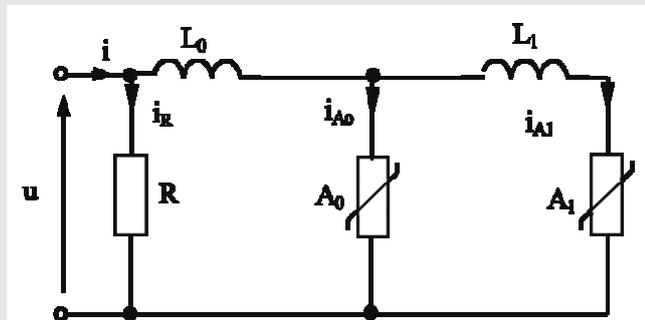


Fig. 3. Simplified IEEE substitute scheme of metal oxide surge arresters

A simplified version of substitute scheme of metal oxide surge arresters recommended by the IEEE (Fig. 1) is shown in Figure 3. The structure of the proposed model with minor adjustments to give accuracy to the dynamic behavior of the metal oxide surge arresters. The two resistance in parallel with inductance are removed. Only one resistance between the input terminals is connected. The operating principle is quite similar to that of the full IEEE model placed in Figure 1 [13].

The current-voltage characteristics of varistors A_0 and A_1 are determined by using equations (1) and (2). To calculation of the inductances L_0 and L_1 the following equations can be used (values in μH):

$$L_1 = \frac{1}{4} \frac{U_{r\ 1/T_2} - U_{r\ 8/20}}{U_{r\ 8/20}} U_n \quad (13)$$

$$L_0 = \frac{1}{12} \frac{U_{r\ 1/T_2} - U_{r\ 8/20}}{U_{r\ 8/20}} U_n \quad (14)$$

where:

U_n – rated voltage of surge arrester, V,
 $U_{r\ 1/T_2}, U_{r\ 8/20}$ – residual voltage for surge current 10 kA with shapes: $1/T_2 \mu\text{s}$ and $8/20 \mu\text{s}$ respectively, V.

The proposed criteria does not take into consideration any physical characteristic of the arrester. Only electrical data are needed. The inductance L_0 in the model represents the inductance associated metal oxide surge arrester elements. And the inductance is very small, L_0 was set a small value, during the impulse current tests, special care was taken to minimize lead inductance. The inductance L_1 is the inductance associated with magnetic fields in the immediate vicinity of the arresters. The function of the inductive element is to characterize the model behavior with respect to lightning surges. The voltage across in the surge arrester reaches a peak before the current reaches its peak.

The equations (13), (14) are based on the fact that parameters L_0 and L_1 are related to the roles that these elements have in the model. Since the function of the inductive elements is to characterize the model behavior with respect to fast surges. It seemed logical to define these elements by means of data related to arrester behaviour during fast voltage surges.

The current-voltage equations for the substitute scheme presented in Figure 3 can be written as follows:

$$u(t) - L_0 \frac{d[i_{A_0}(t) - i_{A_1}(t)]}{dt} - L_1 \frac{di_{A_1}(t)}{dt} - u_{A_1}(t) = 0 \quad (15)$$

$$u(t) - L_0 \frac{d[i_{A_0}(t) - i_{A_1}(t)]}{dt} - u_{A_0}(t) = 0 \quad (16)$$

$$u(t) - R i_R(t) = 0 \quad (17)$$

$$i(t) - i_R(t) - i_{A_0}(t) - i_{A_1}(t) = 0 \quad (18)$$

Nonlinear equation systems (10)–(12) and (15)–(18) can be solved by use of the Newton’s method after differentiation of equations using trapezoidal method.

4. RESULTS OF MODELLING

Using the models above, voltage-current dependencies of the surge arrester type PEXLIM P 96 were determined. Those arresters are used for overvoltage protection of devices in electrical power systems of rated voltage 110 kV [14]. Residual voltages of the experimental surge arrester are presented in Table 1.

Parameters of linear elements of the full model of arrester calculated by use of the equations (5)–(9) are as follows: $L_0 = 0.2 \text{ mH}$, $L_1 = 15 \text{ mH}$, $R_0 = 100 \text{ W}$, $R_1 = 65$, $C = 100 \text{ pF}$.

Table 1
Residual voltages of surge arresters of type PEXLIM P 96 [15]

Type of the surge arrester	Rated voltage U_n , kV	Continuing operating voltage U_c , kV	Residual voltage with different waveforms for discharge current values, kV					
			1/5 μ s	8/20 μ s	30/60 μ s			
			10 kA	5 kA	10 kA	20 kA	1kA	2 kA
PEXLIM P 96	96	77	232	208	219	240	188	194

The values of inductances of the simplified model presented in Figure 3 calculated by use of equations (13) and (14) are as follows: $L_0 = 0.5$ mH, $L_1 = 1.3$ mH. The voltage-current dependencies of the varistors A_0 and A_1 determined by use of formulas (1)–(4) are presented in Figure 4.

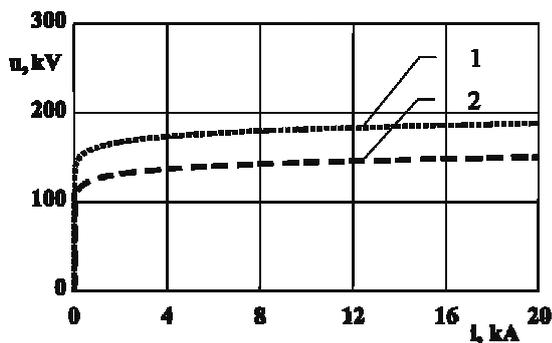


Fig. 4. Current-voltage dependencies of the varistors A_0 and A_1 of full and simplified IEEE model of the experimental surge arrester: 1 – $U_{A_0} = f(i_{A_0})$, 2 – $U_{A_1} = f(i_{A_1})$

Time course of voltages and voltage current dependencies during flow of current impulses in the surge arrester were determined. Shapes of the current impulses are defined by times $T_1/T_2 = 8/20 \mu$ s, $4/10 \mu$ s, where: T_1 – time till maximum, T_2 – time till half of the peak, and maximal value of impulse currents is equal to 5 kA, 10 kA and 20 kA. Time courses of the currents are represented by dependencies:

$$i(t) = 2.18 I_m \exp(-0.065t) \sin(0.107t) \text{ for } 8/20 \mu\text{s} \quad (19)$$

$$i(t) = 2.07 I_m [\exp(-0.14t) - \exp(-0.58t)] \text{ for } 8/20 \mu\text{s} \quad (20)$$

where:

I_m – maximal value of current, A,

t – time, μ s.

The time-voltage and current-voltage dependences for experimental metal oxide surge arresters type PEXLIM P 96 simulated by use of full IEEE model during the current strokes with different shapes are presented in Figure 5.

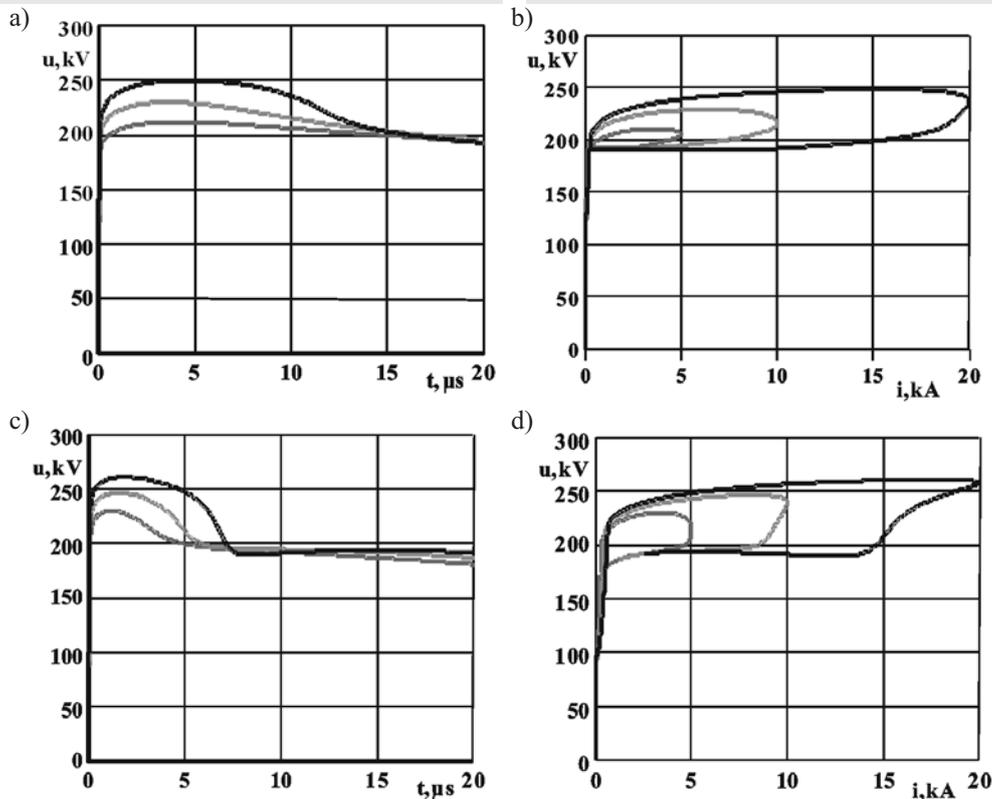


Fig. 5. Voltage-time and voltage-current dependences for metal oxide surge arresters type PEXLIM P 96 simulated by use of full IEEE model for the current strokes with different shapes and maximal values: 5 kA, 10 kA and 20 kA: a, c) time-voltage characteristics; b, d) current-voltage dependencies; a, b) current stroke 8/20 μ s; c, d) current stroke 4/10 μ s

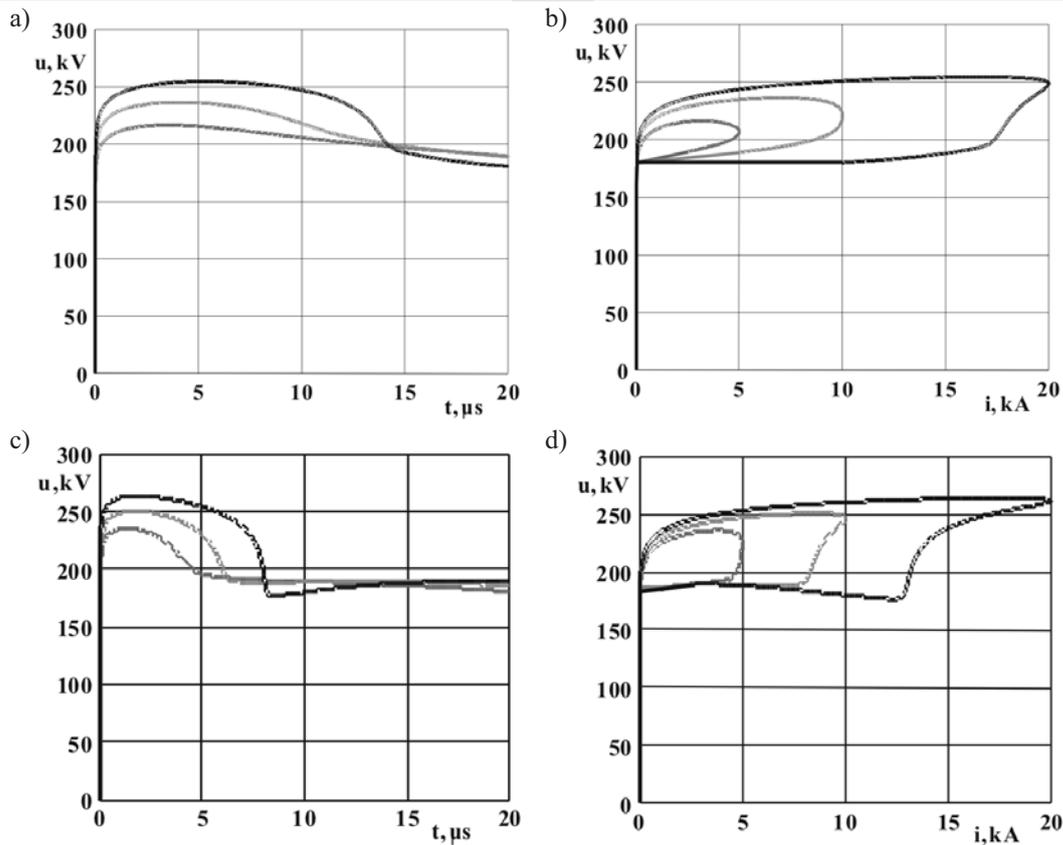


Fig. 6. Voltage-time and voltage-current dependences for metal oxide surge arresters type PEXLIM P 96 simulated by use of simplified IEEE model for the current strokes with different shapes and maximal values: 5 kA, 10 kA and 20 kA: a, c) time-voltage characteristics; b, d) current-voltage dependencies; a, b) current stroke 8/20 μ s; c, d) current stroke 4/10 μ s

Calculation results of this dependencies performed by use of the simplified IEEE model are presented in Figure 6. Presented the results of calculations have been obtained solving of the equation systems (10)–(12) and (15)–(18) by use of MATLAB software.

From simulation results it is possible to see that voltage-time courses are depended form shapes of current strokes. Maximal values of residual voltages on the surge arrestes is depended not only from maximal values of the current strokes and also from time courses of currents.

Calculation errors were determined in order to compare the results of simulations of current-voltage dependencies of surge arrester by use of selected mathematical model. They were calculated by dividing the differences of values of theoretical and experimental maximal values of residual voltages and experimental value of residual voltage of surge arrester. The errors related to simulations of current-voltage dependencies of the experimental surge arrester by use of the full and simplified model of surge arresters performances are shown in Figure 7. They were calculated using calculation results presented in Figures 5 and 6.

It is possible to see from errors of calculations maximal values which is presented in Figure 7 that in all the cases model results that full IEEE model has much lower errors than simplified model. It is also to note, that due to proposed adjustment mechanism, the errors for lightning discharge currents may be only positive. The results obtained are good

and they have good match with catalogue guarantee protective characteristics. Some small difference appeared between the computing and catalogue results. As general it may express that the IEEE model of surge arresters can be recommended, one and then it is good to used for simulation lightning and switching overvoltages.

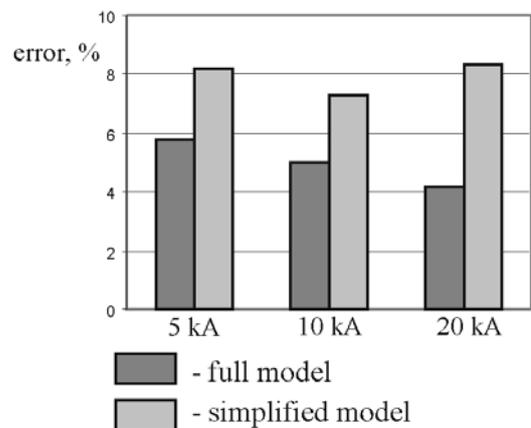


Fig. 7. Errors of calculations of maximal values of residual voltages for the three experimental surge arresters for current strokes of 8/20 μ s determined by use of full and simplified IEEE model of surge arresters

5. CONCLUSIONS

From among numerous models of surge arresters one was selected, whose parameters can be determined only on the basis of their dimensions and results of investigations published in the catalogues. Two versions of this model were used for computer simulations of voltage-time and voltage-current dependencies of high voltage surge arresters where are used in electric power systems of 110 kV. Theoretical maximal values of residual voltages obtained for different current shapes and peak values were compared to the experimental data placed in the catalogue. The errors of calculations for the full model are smaller than for the simplified one, but generally the maximal values of error are smaller than 6%. Presented results of calculations confirm that both the full IEEE model as well as the simplified one reflect property of dynamic characteristics of surge arresters.

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