Simulation of Metal Oxide Surge Arresters Behavior

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Abstract— **Metal Oxide surge arresters are used to protect medium and high voltage systems and equipment against lightning and switching overvoltages. Measurements of the residual voltage of the metal oxide surge arrester indicate dynamic characteristics, and specifically, the residual voltage increases as the current front time descends and the residual voltage reaches its maximum before the arrester current reaches its peak. For these reasons, the metal oxide surge arresters cannot be modeled by only a non-linear resistance, since its response depends on the magnitude and the rate of rise of the surge pulse. Several frequent dependent models have been proposed, in order to simulate this dynamic frequency-dependent behavior. In the current work three modes – IEEE, Pinceti-Gianettoni and Fernadez-Diaz – are examined using PSCAD. The residual voltage of each model, implying 5kA, 10kA and 20kA 8/20μs impulse current, is compared with the manufacturers' datasheet. The models were also used to study the lightning performance of a distribution line; the arresters were implemented on every pole and was calculated their failure probability. The results show that all the models function with a satisfactory accuracy; the differences among the models arise in the difficulties of the parameters' estimation.**

I. INTRODUCTION

Metal oxide (MO) surge arresters are used to protect equipment in electrical systems against internal and external overvoltages. Several different types of arresters are available (e.g. gapped silicon carbide, gapped or non-gapped metal-oxide) and all perform in a similar manner: they function as high impedances at normal operating voltages and become low impedances during surge conditions [1-4]. An ideal arrester must conduct electric current at a certain voltage above the rated voltage, hold the voltage with little change for the duration of overvoltage and substantially cease conduction at very nearly the same voltage at which conduction started [5].

Even though a great number of arresters, which are gapped arresters with resistors made of silicon-carbide (SiC) are still in use, the arresters installed today are almost all metal-oxide arresters without gaps, which means arresters with resistors made of metal-oxide [6]. Constructively, MO surge arresters have a simple structure, comprising one or more columns of cylindrical blocks varistors. A ZnO 20kV surge arrester is shown in Fig.1. They have extremely non-linear characteristics and when they operate, they let through less power-frequency current than SiC arresters. An MOV arrester will let through only the current impulse caused by the overvoltage and does not have power-frequency follow current. This allows MOV arresters with less energy capability to be used when replacing SiC arresters [7].

Figure 1. A Zno 20kV surge arrester

II. V-I CHARACTERISTICS OF MO SURGE ARRESTERS

The MO varistor obeys the equation [1, 2]:

$$I = kV^{\alpha}, \; a>1 \tag{1}$$

where

- I current through arrester
- V voltage across arrester
- k ceramic constant (depending on arrester type)
- a nonlinearity exponent (measure of nonlinearity).

V-I characteristic must be determined from measurements made with brief pulse currents, such as an 8/20 μs waveshape, in order to avoid effects of heating the varistor. Further, the interval between the consecutive surges in the laboratory must be sufficiently long to allow the varistor to return to room temperature before the next surge is applied [5].

Data and measurements on characteristics of MO surge arresters indicate a dynamic behavior of the arresters; the residual voltage of the arrester depends on the current surge waveform shape. Analytically, the residual voltage increases as the current front time decreases [2, 4]. This increase of the residual voltage could reach approximately 6% when the front time of the discharge current is reduced from 8 to 1.3μs [7-9]. Another dynamic characteristic is that the residual voltage reaches its maximum before the current maximum.

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III. MO Surge Arresters Models

MO surge arresters cannot be modeled by only a non-linear resistance, since its response depends on the magnitude and the rate of rise (slope) of the surge pulse. MO arresters behave differently for various surge waveforms, depending each time on the magnitude and the rate of rise of the surge.

Several frequent dependent models of MO surge arresters have been proposed, in a way that the model simulation results correspond to the actual behavior of the arrester. The difficulties for each model arise in the estimation of its parameters, since are demanded manufacturers' data and apply of iterative procedure. The existing models [9-11] are mainly differing in the parameters' estimation procedure, but all are efficient to simulate the frequency-depended behavior of the arresters. In this work are presented three of these models and are simulated by appropriate computer program.

A. The IEEE model

The IEEE Working Group 3.4.11 [9] proposed the model of Fig. 2, including the non-linear resistance A_o and A_1, separated by a R-L filter. For slow front surges the filter impedance is low and the non-linear resistances are in parallel. For fast front surges filter impedance becomes high, and the current flows through the non-linear resistance A_o.

Since the characteristic A_o has higher voltage for a given current, the result is the higher frequency the higher residual voltage.

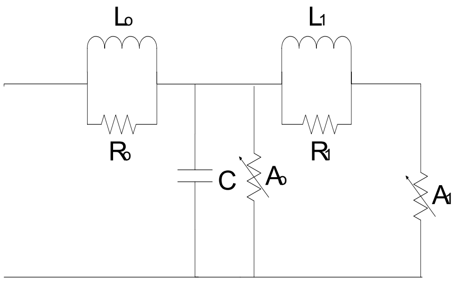

Figure 2. The IEEE model [8]

The inductance L_1 and the resistance R_1 comprise the filter between the two varistors, since the inductance L_o is associated with magnetic fields in the vicinity of the arrester. R_o stabilizes the numerical integration and C represents the terminal-to-terminal capacitance. The equations for the above parameters and the per unit V-I characteristic of the varistors are given as [9]:

$$L_1 = (15d)/n \quad \mu\text{H} \tag{2}$$

$$R_1 = (65d)/n \quad \Omega \tag{3}$$

$$L_o = (0.2d)/n \quad \mu\text{H} \tag{4}$$

$$R_o = (100d)/n \quad \Omega \tag{5}$$

$$C = (100n)/d \quad \text{pF} \tag{6}$$

where d is the length of arrester column in meters and n is the number of parallel columns of meta-oxide disks.

B. Pinceti– Gianettoni Model

It is based on IEEE with some differences. There is no capacitance and the resistance R_o and R_1 are replaced by one resistance (about 1MΩ) at the input terminals, as Fig. 3 shows. The non-linear resistors are based on the curves of [9]. The inductances L_o and L_1 are calculated using the equations [10]:

$$L_1 = \frac{1}{4} \cdot \frac{V_{r(1/T_2)} - V_{r(8/20)}}{V_{r(8/20)}} \cdot V_n \ \mu\text{H} \tag{7}$$

$$L_2 = \frac{1}{12} \cdot \frac{V_{r(1/T_2)} - V_{r(8/20)}}{V_{r(8/20)}} \cdot V_n \ \mu\text{H} \tag{8}$$

where V_n is the arrester's rated voltage, $V_{r(8/20)}$ is the residual voltage for a 8/20 10kA lightning current and $V_{r(1/T2)}$ is the residual voltage for a $1/T_2$ 10kA lightning current.

The advantage of this model in comparison with the IEEE model is that there is no need for physical characteristics of the arresters but only electrical data, given by the manufacturer.

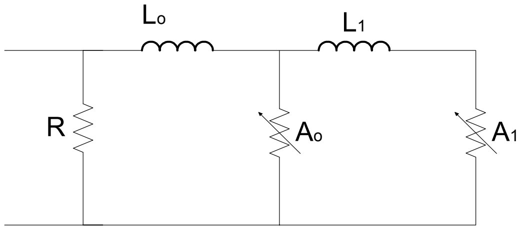

Figure 3. The Pianceti – Gianettoni Model [10]

C. The Fernadez – Diaz Model

It is also based on IEEE model. In this model A_o and A_1 are separated by L_1, while L_o is neglected (Fig.4). C is added in arrester terminals and represented terminal-to-terminal capacitance of the arrester.

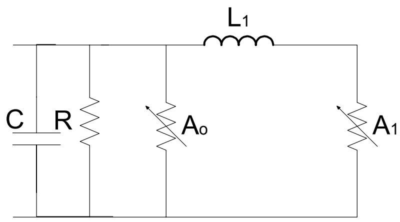

Figure 4. The Fernadez – Diaz Model [11]

This model does not require iterative calculations since the required data are obtained from the manufacturer's datasheet. The procedure for the computation of the parameters is given in [11]. The V-I characteristics for A_o and A_1 are calculated using manufacturers' data and considering a ratio I_o to I_1 equal to 0.02. The inductance L_1 is given as:

$$L_1 = nL_1' \tag{9}$$

where n is a scale factor and L_1' can be found in [11], computing the percentage increase of the residual voltage as:

$$\Delta V_{res}(\%) = \frac{V_{r(1/T_2)} - V_{r(8/20)}}{V_{r(8/20)}} \cdot 100 \qquad (10)$$

where $V_{r(8/20)}$ is the residual voltage for a 8/20 lightning current and $V_{r(1/T2)}$ is the residual voltage for a $1/T_2$ lightning current with the nominal amplitude.

IV. Simulation Results

The simulations for each model were performed using PSCAD program for a one-column 20 kV MO arrester, with height 260mm. In Tables I-III are shown the computed parameters for each model.

TABLE I.
Parameters for the Ieee Model

L_1	3.9 μH
R_1	16,9 Ω
L_o	0,052 μH
R_o	26 Ω
C	384,6 pF

TABLE II.
Parameters for the Pinceti-Gianettoni Model

L_1	0.317 μH
L_o	0,106 μH
R	1 MΩ

TABLE III.
Parameters for the Fernadez-Diaz Model

L_1	1.07 μH
C	94.74
R	1 MΩ

The residual voltage waveforms of each model for three impulse currents 8/20μs (5kA, 10kA, 20kA) are shown in Figures 4-6.

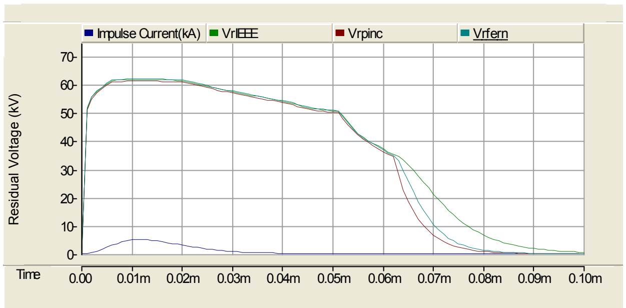

Figure 4. Residual Voltage for a 5kA current impulse (8/20μsec)

The simulation results for each model are compared with the manufacturer's data (Table IV). The relative error is computed by the equation:

$$e = \frac{Vr_{simulation} - Vr_{manufacturer}}{Vr_{manufacturer}} \cdot 100\% \qquad (11)$$

where $Vr_{simulation}$ is the residual voltage from the simulation and $Vr_{manufacturer}$ is the residual voltage given by the manufacturer datasheet.

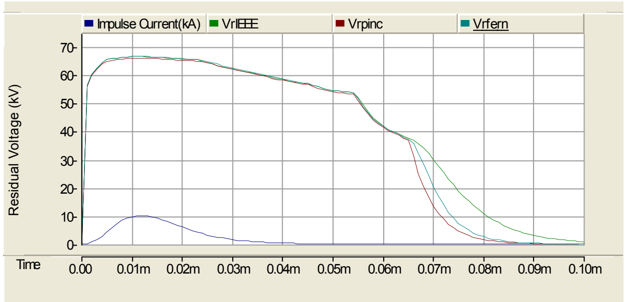

Figure 5. Residual Voltage for a 10kA current impulse (8/20μsec)

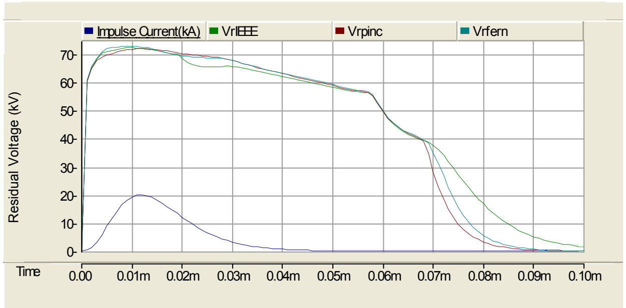

Figure 6. Residual Voltage for a 20kA current impulse (8/20μsec)

All the simulated models seem to be efficient and they reproduce with a good accuracy the peak residual voltage of the manufacturer's datasheet. The Pincetti – Giannettoni model and the Fernadez-Diaz model are simpler, since they don't need any physical characteristic of the arresters or an iterative procedure for the parameters' calculation.

V. Practical Application of the Models

MO surge arresters are installed in distribution or transmission lines in order to protect them by direct or nearby strokes and to reduce the failure rate. The lightning energy absorbed by arresters is given by the equation:

$$E = \int_{t_o}^{t} u(t) \cdot i(t)dt \qquad (12)$$

where:

$u(t)$ is the residual voltage of the arrester in kV and
$i(t)$ is the value of the discharge current through the arrester in kA

When the absorbed energy by the arresters exceeds their maximum acceptable level of energy, then they will fail (damage). The arresters' failure probability is given as [12]:

$$P = \int_{T_r}^{\infty} \left\{ \int_{I_L(T_t)}^{\infty} f(I_p)dI_p \right\} g(T_t)dT_t \qquad (13)$$

where:

$I_L(T_t)$ is the minimum stroke peak current in kA required to damage the arrester, when lightning hits on a phase conductor, depending on each time-to-half value,
$f(I_P)$ is the probability density function of the lightning current peak value,
$g(T_t)$ is the probability density function of the time-to-half value of the lightning current

TABLE IV.
RESIDUAL VOLTAGES AND RELATIVE ERRORS FOR EACH MOD

I (kA)	Residual Voltage (kV)						
	Manufacturers' datasheet	IEEE model	*e* (%)	Pinceti-Gianettoni model	*e* (%)	Fernadez – Diaz model	*e* (%)
5	60.80	61.73	1.53	61.17	0.61	61.94	1.88
10	65.20	66.41	1.86	65.98	0.78	66.57	2.10
20	71.20	72.18	1.38	71.82	0.87	72.65	2.04

In order to examine the performance of each arresters' model in practical applications, it was calculated the arresters' failure probability in a 20kV distribution line (Fig.6), implementing one model each time. It is assumed that the arresters, which have energy withstand capability 1.2kJ/kV MCOV, are installed on every pole on all phases. The frequency distributions and the parameters of the lightning current are based on the measurements performed by Berger in Monte San Salvatore [13]. The time to crest value of the lightning current is constant at 2μs, since its influence is negligible in comparison with the time-to-half value, which is varied from 10μs to 1000μs.

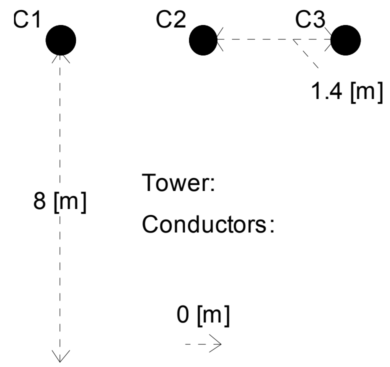

Figure 6. Distribution line model

The simulations were performing using PSCAD. The waveforms of the arresters' terminal voltage and the current flowing through them taken by the PSCAD simulation, are used to calculate the energy dissipated by the arresters, which when exceeds the arresters energy capability, a fault is occurred.

In Table V are given the results for three different tower footing resistances. The three models give efficient results, without great differences. The failure probability increases as grounding resistance increases, in the same way for all the models.

TABLE V.
ARRESTERS' FAILURE PROBABILITY

	Arresters Failure Probability		
Grounding Resistance	10Ω	40Ω	80Ω
IEEE model	30.1%	32.4%	36.1%
Pinceti model	28.2%	30.5%	34.7%
Fernadez model	29.4%	31.2 %	35.6 %

Fig. 7 represents the simulation results in the same diagram. IEEE model gives a little greater probability, mainly due to the fact that the area under the voltage curve is bigger, so the absorbed energy will be greater. This results to a greater failure probability. However, the computed results show that all the models are appropriate for lightning performance simulation and failure probability estimation; which model it will be chosen each time depends on the data that are available.

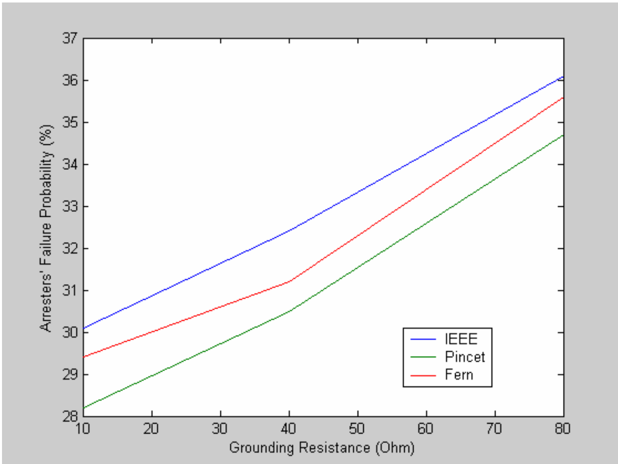

Figure 7. Arresters' Failure Probability for each model vs Grounding Resistance

VI. CONCLUSIONS

In this paper are examined three MO surge arresters' frequency depended models, which differ in the calculation and adjustment of their parameters. Using PSCAD were computed the residual voltages of each model, applying 8/20μs impulse current and the simulation predictions were compared with the manufacturer's data. The three models seem to reproduce efficiently the arresters' residual voltage, presenting an acceptable error. The models were also implemented in a 20kV distribution line, in order to estimate the arresters' failure probability. The analysis showed that all the models have an efficient dynamic behavior and they can be used to examine the lightning performance of electrical installations. The main difference between the models consists in the procedure of parameters' calculation.

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