

Metal-oxide surge arrester model for fast transient simulations

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Abstract - Metal-oxide surge arresters have dynamic characteristics that are significant for overvoltage coordination studies involving fast front surges. Several models with acceptable accuracy have been proposed to simulate this frequency-dependent behavior. Difficulties arise in the calculation and adjustment of the model parameters: in some cases iterative procedures are required, in others the necessary data are not reported on manufacturers' datasheets. A simplified model for zinc oxide surge arresters has already been developed, on the basis of the frequency-dependent model recommended by the IEEE WG.3.4.11. In this paper, a different, also straightforward approach, for the generation of the IEEE model parameters from published manufacturer's data, is presented. The model was verified for several medium voltage arresters from different manufacturers. The simulations were performed with the Alternative Transient Program (ATP) and the results were compared with both the data reported on the manufacturer's catalogue and experimental data acquired in the high voltage laboratory. For a fast front current surges with front times of up to 1 μs , the model has an acceptable voltage response accuracy of about 1.5%.

Keywords: Metal Oxide Surge Arresters, Frequency-Dependent Model, Insulation Coordination, EMTP.

I. INTRODUCTION

Metal oxide surge arresters (MOSA) are widely used as protective devices against switching and lightning overvoltages in power electrical systems. Powerful simulation tools, such as the Electromagnetic Transient Program (EMTP), are nowadays of standard application to evaluate insulation coordination in those systems. Appropriate mathematical and/or circuitous models for these arresters are therefore of great interest, because they let assess their behavior under these voltage stresses.

A unique model for MOSA to evaluate all the possible transient perturbations in power systems would surely be so complicated and require so much simulation resources, that its implementation would be unpractical. Therefore, by the election of an appropriated model for a MOSA, the type of transient overvoltage to be evaluated should be attended. Switching surge studies could be performed by representing the MOSA only with their non-linear V-I characteristics [1]. However, MOSA have dynamic characteristics that are significant for lightning and other fast wave front surges. For current surges with front times

faster than about 10 μs , the residual voltage across the arrester increases as the time to crest of the arrester discharge current decreases, and the arrester residual voltage reaches a peak before the arrester discharge current reaches its peak. This increase of the residual voltage could reach approximately 6% when the front time of the discharge current is reduced from 8 to 1.3 μs . Indeed, the voltage across the arrester is not only a function of the discharge current, but also of the rate of its rise. These characteristics, referred as frequency-dependent behavior, require a more sophisticated model than the simple static non-linear resistance.

Several models [1, 2, 3] have been proposed to simulate these dynamic characteristics. While these models have an acceptable accuracy, difficulties arise in the calculation and adjustment of their parameters: in some cases iterative procedures are required, in others the necessary data are not reported on manufacturers' datasheets. A simplified model for zinc oxide surge arresters [3] has already been developed, on the basis of the frequency-dependent model recommended by the IEEE WG.3.4.11 [1].

In this paper, a simplified model of that proposed by the IEEE is considered, and a different, also straightforward approach for the generation of its parameters starting from manufacturer's data, is proposed. The suggested mechanism for the parameters adjustment is explained, and the results verified through simulations with the EMTP and experimental measurements in the high voltage laboratory [5].

It should also be mentioned, that for arrester discharge currents with time-to-crest shorter than 4 μs , voltage spikes appear on the front of the arrester residual voltage waveform [4]. However these voltage spikes do not exceed the residual voltage for currents with time-to-crest more than 0.5 μs . These spikes are therefore out of the proposed model's scope and will not be considered for the adjustment procedure.

II. THE FREQUENCY-DEPENDENT MODEL

The frequency-dependent model, such as proposed by IEEE in [1], is shown in Fig.1. The two non-linear resistances A_0 and A_1 , are separated by a RL filter. For arrester discharge currents with slow rising time, the influence of the filter is negligible; thus A_0 and A_1 are essentially in parallel and characterize the static behavior of the MOSA. For fast rising surge currents, the impedance of the filter becomes more significant, indeed the inductance L_1 derives more current into the non-linear

branch A0. Since A0 has a higher voltage for a given current than A1, the model generates a higher voltage between its input terminals, what matches the dynamic characteristics of MOSAs.

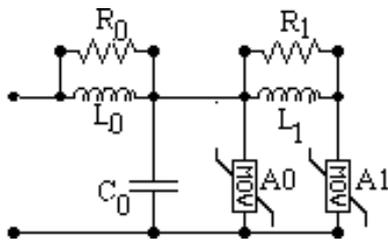


Fig. 1: Frequency-dependent model, as proposed in [1].

The proposed curves for A0 and A1 are shown in Fig.2. The per-unit values are referred to the peak value of the residual voltage measured during a discharge test with 10 kA lightning current impulse ($U_{r,8/20}$). These curves are to be adjusting to get a good fit with the published residual voltages for switching surge discharge currents. The inductance L_0 represents the inductance associated with the magnetic fields in the immediate vicinity of the arrester. The resistor R_0 is used to avoid numerical oscillations when running the model with a digital program. The capacitance C_0 represents the external capacitance associated to the height of the arrester. Starting from the physical dimensions of the arrester, some formulas are given in [1] to calculate L_0 , R_0 , C_0 and R_1 . The parameter L_1 has the most influence on the result and a formula, starting from the physical dimensions, is also suggest in [1]. However this constitutes only an initial value, and L_1 should be adjusted by a try- and error procedure to match the residual voltages for lightning discharge currents published in manufacturer's catalogue. This model can give satisfactory results for discharge currents within a range of times to crest for $0.5 \mu s$ to $45 \mu s$ [1]. A different, straightforward approach to determine L_1 , starting from electrical data of the arrester, is also proposed in [3]. In this case, the authors report relative errors between calculated and measured residual voltages lower than 4.5% for discharge currents with time-to-crest ranging from $1 \mu s$ to $30 \mu s$.

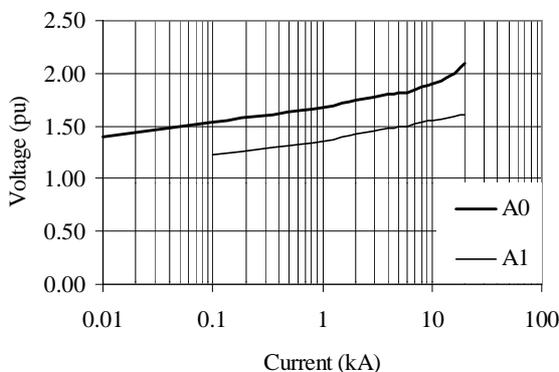


Fig.2 : Non-linear characteristic for A0 and A1. The voltage is in p.u. referred to the $U_{r,8/20}$.

III. NEW PROPOSAL TO THE MODEL ADJUSTMENT

The proposed model is shown in Fig.3 and derives from that in [1]. It is intended for the simulation of the dynamic characteristics for discharge currents with front times starting from $8 \mu s$. As in [3], between the non-linear resistances A0 and A1 only the inductance L_1 is taken into account. R_0 and L_0 are neglected. C_0 represents the terminal-to-terminal capacitance of the arrester. The resistance R in parallel to A0 is intended to avoid numerical oscillations. The model in Fig.3 works essentially in the same way as that proposed in [1].

To explain the principle of the new proposal, it will be referred in a first approach to only one arrester valve block. The conclusions are later generalized for a complete MOSA.

A. Assumptions for the parameters adjustment.

The following principle explains the adjustment procedure proposed in this contribution: The non-linear characteristics of A0 and A1 are to be adjusted to match the residual voltages for the lightning discharge currents [6] of the protection V-I-characteristic provided by the manufacturer; besides, an additional condition should be respected: the ratio (γ) of the currents I_0 to I_1 through A0 and A1 respectively remains constant all over the voltage range of their protection characteristic. If we now consider currents of a given amplitude but front times faster than $8 \mu s$, this additional restriction guaranties, that the percent voltage increase between the input terminals depends only of the inductance L_1 . The election of L_1 can then succeed straightforward through the use of predefined curves, which are generated in the next item.

B. Selections curves for L_1

Two ideal, elementary valve blocks with a rated voltage of 1 kV for lightning discharge currents of 5 and 10 kA respectively were considered. A ratio γ of 0.02 was found to be adequate for the response of the model. Because the value of γ will determine the finally value of L_1 , it will indirectly influence the time lag of the residual voltage peak and indeed the form of the well known [2,3] hysteresis cycle. The Table 1 summarizes the V-I-characteristic for these valve blocks and the currents into the branches A0 and A1.

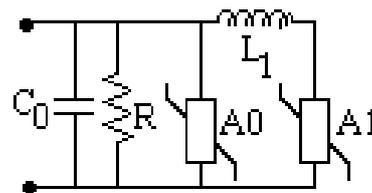


Fig.3 : Proposed model.

Table 1. Maximum residual voltages for elementary valve blocks of 1kV rated voltage with lightning discharge nominal current of 5 and 10 kA. Ratio I_0 to I_1 equal to 0.02.

Maximum residual voltage [kV]		8/20 μ s lightning discharge current [A]		
5kA block	10kA block	I	I_0	I_1
2.87	2.73	1500	30	1470
3.07	2.90	3000	60	2940
3.27	3.07	5000	100	4900
3.60	3.33	10000	200	9800
4.27	3.77	20000	400	19600
5.30	4.53	40000	800	39200

The proposed model for the two ideal elementary valve blocks was implemented in the EMTF. Several simulations for discharge currents of 5 kA and 10 kA respectively and different front times were carried out. Each case was repeated for different values of the inductance L_1 , and in each of them the percent increase of the residual voltage was calculated as:

$$\Delta U_{res} \% = \frac{U_{In,T_1} - U_{In,8/20}}{U_{In,8/20}} \cdot 100 \quad (1)$$

where $U_{In,8/20}$ is the residual voltage for the lightning discharge current of nominal amplitude, and U_{In,T_1} is the residual voltage for a discharge current with front time T_1 and nominal amplitude. A typical result for the 5 kA valve block is shown in Fig. 4.

The types of curves shown in Fig. 4 were redrawn in those of Fig. 5, for both the 5 and 10 kA valve blocks. From these curves in Fig. 5 an appropriate value of L_1 for the model in Fig.3, can be directly and straightforwardly selected, as a function of the percent increase of the residual voltage for a fast rising discharge current.

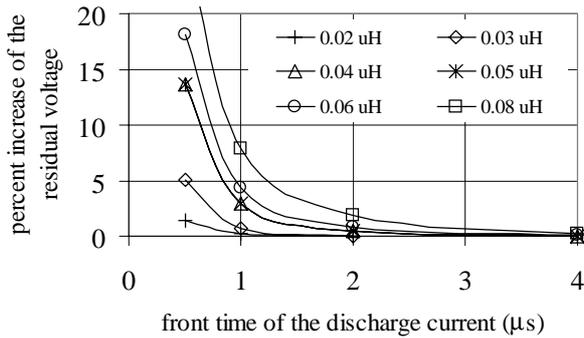


Fig. 4: Increase of the residual voltage in a 5 kA valve block

C. Model for a complete arrester

The model for the just considered 1 kV rate voltage elementary valve block is now extended for a complete arrester. This succeed with the factor n defined as:

$$n = \frac{U_{In,8/20} \text{ for the complete arrester}}{U_{In,8/20} \text{ for the 1 kV valve block}} \quad (2)$$

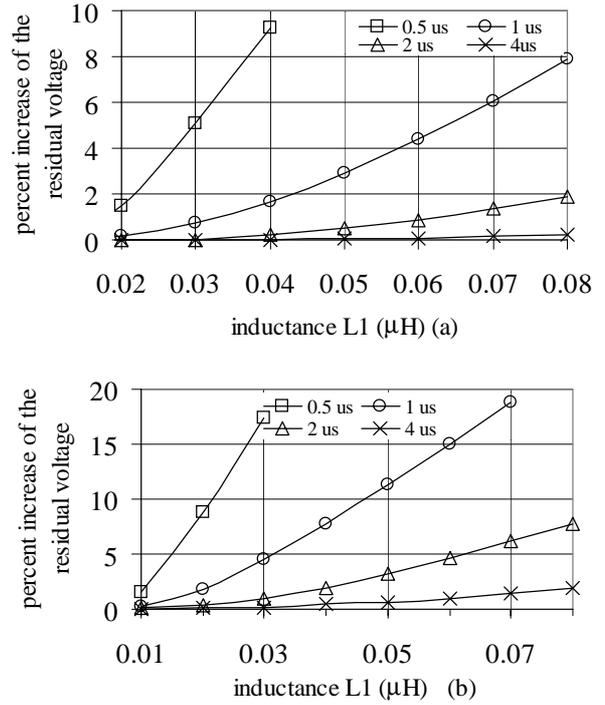


Fig. 5. Selection curves for: (a) 5 kA valve block, (b) 10 kA valve block.

where $U_{In,8/20}$ are the residual voltages for the nominal lightning discharge current for both the complete arrester (manufacturers' data) and the 1 kV valve block (in Table 1). It is important to note, that the scale factor defined in (2) takes into account the residual voltages of the arresters and not the rate voltages of them. It seems logical to use this factor, because the model is intended to represent the protection characteristic of the arrester. Fig. 6 illustrates the mechanism. The names with apostrophes identify the elements of the 1 kV rate voltage valve block, while the others represent the elements of the equivalent circuit for the completed arrester.

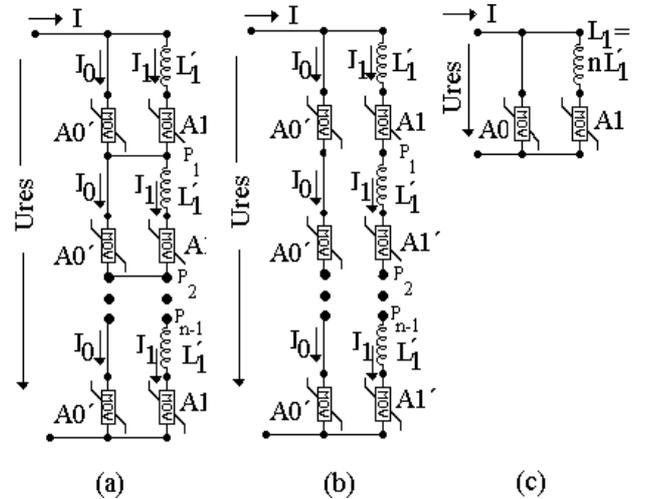


Fig. 6. Deduction of the equivalent circuit for a complete surge arrester.

Basically, n elementary valve blocks are to be connected in serial. Because the n blocks are identical, the voltage distribution across them is uniform, and no current flows between the branches A0' and A1' at the junction points P_1, P_2, \dots, P_{n-1} in Fig. 6(a). Thus follows Fig. 6(b), and finally the equivalent circuit in Fig. 6(c). Here, the inductance L_1 is the serial equivalent of the n inductance L'_1 , which was calculated with the curves in Fig.5. The parallel of A0 and A1 in Fig. 6(c) represent the V-I protective characteristic of the completed arrester, which is given in the manufacturers' catalogue.

D. Resume of the proposed adjustment method

The following steps resume the author's new proposal to adjust the simplified model in Fig.3. All the necessary data can to be obtained from the manufacturer's datasheets.

- 1.- With the residual voltages ($U_{8/20}$) for lightning discharge currents ($I_{8/20}$) over the protective characteristics of the arrester, calculate the non-linear characteristics for A0 and A1, taking into account that the ratio I_0 to I_1 (γ) is equal to 0.02 and I_0 plus I_1 is equal to $I_{8/20}$ for all the points over the curve.
- 2.- With (1), calculate the percent increase of the residual voltage ($\Delta U_{res} \%$) for the nominal current of the arrester.
- 3.- With $\Delta U_{res} \%$ and T_1 , select from the correspondent curve in Fig. 5, the appropriate value for L'_1 .
- 4.- With the scale factor (2), determine $L'_1 = n.L_1$.
- 5.- The terminal-to-terminal capacitance C_0 is given by:

$$C_o = \frac{100}{d} \quad (3)$$

where C_0 is in pF and d is the overall height of the arrester in m.

- 6.- Finally, for the resistance R assume 1 M Ω for medium voltage arresters and 10 M Ω for the high voltage ones. This resistance is intended to avoid numerical oscillations while simulating with digital programs, and its value is not critical.

IV. MODEL VALIDATION

A. Numerical validation

The simplified model in Fig.3 was adjusted for several medium and high voltage arresters of 5 and 10 kA discharge nominal current (I_n) from different manufacturers, adopting the proposed adjustment mechanism. Catalogue data for some illustrative cases are shown in Table 2.

Table 2. Manufacturer's data.

Type, I_n [kA]	U_{rate} kV	Residual voltage [kV] for discharge currents [kA]:				
		1/5us I_n	8/20 us			
			3	5	10	20
Manuf.1, 5	12	40.8	36.8	39.2	43.4	51.0
Manuf.2, 10	20	55.0		48.0	51.0	57.0
Manuf.3, 10	111	282		250	266	298

The models were implemented on the EMTP. Branch cards type-92 [7] were used to simulate the non-linear characteristics of A0 and A1, and the surge source type-15 [8] for the discharge currents.

Table 3 summarizes the percent errors in the residual voltages for the three cases of table 2. In all the cases, the model results were within 1.7% of the published data, for front times of the discharge currents ranging from 8 μ s to 1 μ s and therefore lower than in [1, 3]. It is also to note, that due to the proposed adjustment mechanism, the errors for lightning discharge currents may only be positive.

Table 3. Per-cent errors of the residual voltages for different discharge currents referred to the values reported in Table 2.

Case	Type	e% of the residual voltage for discharge currents:			
		1/5us	8/20 us		
		I_n [kA]	5 [kA]	10 [kA]	20 [kA]
1	Manuf. 1	+0.03	+0.10	+0.29	+0.53
2	Manuf. 2	+1.56	+0.07	+0.27	+0.47
3	Manuf. 3	+1.69	+0.06	+0.21	+0.37

V. CONCLUSIONS

A new procedure for the adjustment of the parameters of a simplified model for metal oxide surge arresters, derived from that in [1], is presented. All the required data are to be found in manufacturer's catalogue or alternatively can also be obtained in experimental measurements. In this way, the selection procedure results more flexible, but nevertheless no more complicate, than those proposed in [1, 2, 3]. The adjustment mechanism succeeds straightforward; no iterative calculations are required. The model was verified experimentally [5] and numerically for some arresters of medium and high rate voltage. For fast front current surges with front times of 8 μ s and up to 1 μ s, the model has a maximal error of 1.7 % in the voltage response, and is therefore appropriate for overvoltage coordination studies.

VI. REFERENCES

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[7] ATP Rulebook – XIX.I- “ZNO FITTER” to punch Type-92 ZnO branch cards.
 [8] ATP Rulebook – VII.A

VII. APPENDIX

Example of parameter selection for the arrester type Manufacturer 1, 12 kV, 5 kA.

As an example for the proposed adjustment mechanism, this appendix determines the parameter of the model for the 12 kV, 5 kA Manufacturer 1 arrester shown in Table 2, following the steps in III.D.

1.- The non-linear characteristics for A0 and A1 are calculated, starting from the manufacturer’s data in Table 2 and a γ equal to 0.02. Table 4 shows the results.

Table 4. Non-linear characteristic for A0 and A1.

$U_{8/20}$ [kV]	$I_{8/20}$ [A]	I_0 [A]	I_1 [A]
34.4	1500	30	1470
36.8	3000	60	2940
39.2	5000	100	4900
43.4	10000	200	9800
51.0	20000	400	19600
63.8	40000	800	39200

2.- The percent increase of the residual voltage results:

$$\Delta U_{res} \% = \frac{40.8 - 39.2}{40.8} \cdot 100 = 4.08\% \quad (4)$$

3.- From the curve for a front time of 1 μ s in Fig. 5(a), an inductance L_1 of 0.058 μ H is selected.

4.- The scale factor for this arrester is calculated with (2). It results:

$$n = \frac{39200 \text{ V}}{3270 \text{ V}} = 11.99 \quad (5)$$

and then

$$L_1 = nL_1' = 11.99 \cdot 0.058 = 0.69 \mu\text{H} \quad (6)$$

5.- The overall height of the arrester is 0.438 m. Replacing in (3), the terminal-to-terminal capacitance results:

$$C_0 = \frac{100}{0.438} = 228.3 \text{ pF} \quad (7)$$

6.- Finally, the resistance R is assumed 1M Ω for this medium voltage arrester.

All the parameters are now selected, and the model can be implemented in the EMTP. Figs. 7 show some illustrative results, that were obtained by the simulations.

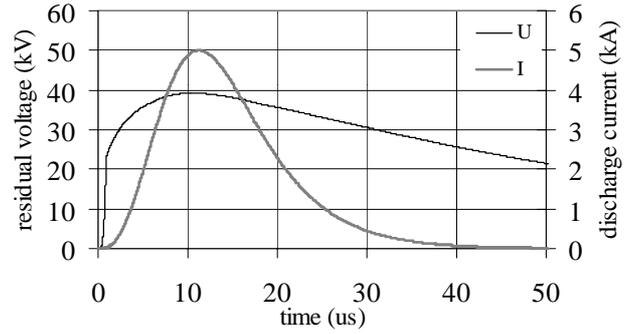


Fig.7(a). Residual voltage for a 5 kA lightning discharge current.

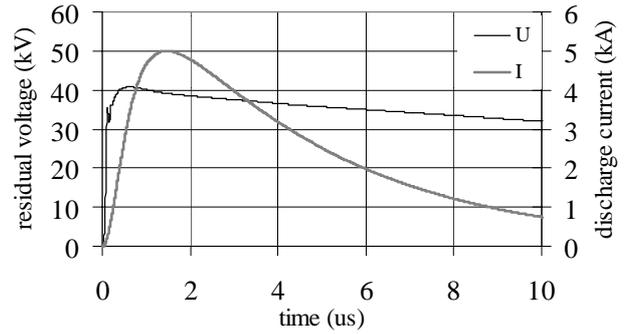


Fig. 7(b). Residual voltage for a 5 kA discharge current with front time 1 μ s.

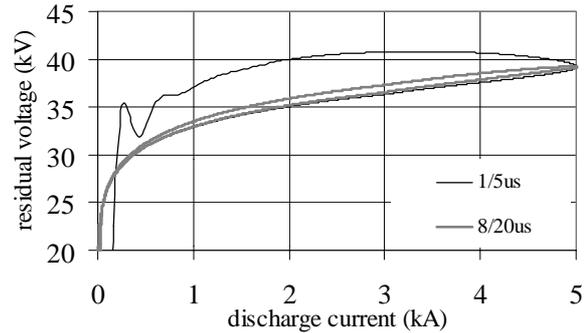


Fig. 7(c) . Dynamic behaviour of the surge arrester Manufacturer 1, 12 kV, 5 kA.