DOI: https://doi.org/10.15407/techned2020.05.049

ADJUSTMENT OF THE MATLAB SURGE ARRESTER MODEL PARAMETERS

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This article proposes a method for the parameters adjustment of the Matlab Simscape library Surge Arrester block. It is based on building of nonlinear V-I characteristic by approximation of residual voltage and impulse current obtained from manufacturer catalogs. Given parameters of the exponential function are checked by transient simulations under impact of standard current impulses on surge arresters. References 14, figure 1, tables 3.
Key words: zinc oxide surge arresters, parameters of mathematical model, residual voltage, impulse of current.

Introduction. Internal and external overvoltages often occur in overhead transmission lines and substations. They can cause damage of equipment in cases when voltage exceeds the insulation level. Analysis of transient processes without taking into account the operation of the surge arresters can show the levels and duration of the overvoltages that affect them [1,2]. This can be useful in a case of choosing ways and means of overvoltage protection.

Installation of surge arrester can provide a limitation of overvoltage to a chosen protective level [3]. One side of the surge arrester is connected to the protected equipment, and the other to the ground. It limits transient voltage during switch commutations, lightning discharges and other disturbances by changing the nature and value of its leakage current.

Modern gapless surge arresters use zinc oxide (ZnO) elements in form of cylindrical blocks that have extremely non-linear voltage-current (V-I) characteristic

$$I = KV^{\beta}, \tag{1}$$

where $K = 1/R$ is the conductance of arrester, β is the measure of non-linearity between *V* and *I*. The measure of non-linearity can also be represented as 1/α.

The parameter *K* depends upon the dimensions of the block, while α, which describes the nonlinear characteristic, depends upon the block material. By altering α and *K*, the arrester can be designed for any conducting voltage and nominal current discharge.

In Matlab Simscape library the nonlinear V-I characteristic of the surge arrester is modeled by a combination of three exponential functions of the form

$$V / V_{base} = k_i \left(I / I_{base} \right)^{1/\alpha_i}, \; i = 1,2,3 \tag{2}$$

where V_{base} is the protection voltage of the surge arrester, I_{base} is the current used to specify the protection voltage. Usually I_{base} takes value 500 A or 1 kA.

The Matlab user guide says that default parameters k and α given in the dialog box fit the average V-I characteristic provided by the main metal-oxide arrester manufacturers and they do not change with the protection voltage. But the parameters of the three segments may need to be tuned to fit the V-I characteristic usually provided in the surge arrester datasheets [4]. The purpose of this article is to verify the accuracy of the initial V-I characteristics and develop a method to adjust V-I curve parameters of the Matlab surge arrester model according to the information from catalogs of their manufacturers. There are researches devoted to arrester model parameters are well known. However, they are mainly concerned to identification of models parameters and comparison of different model types using measurement result and simulation [5–7].

Surge arrester V-I characteristic curves. The Figure presents typical electrical characteristic of a ZnO surge arrester [8]. This characteristic has four specific points. Point *1* corresponds to the maximum

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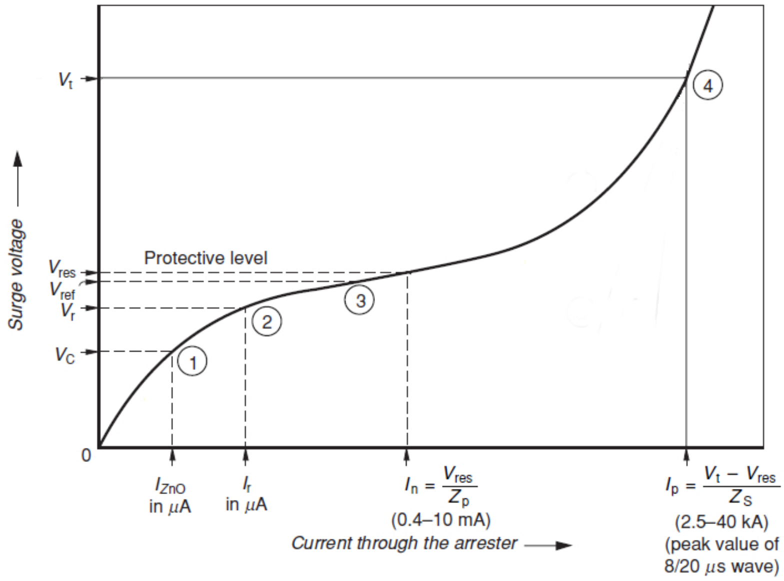
continues operation voltage (MCOV) V_c – the maximum designated root-mean-square (rms) value of power-frequency voltage that may be applied continuously between the terminals of the arrester. It can be applied continuously (≥ 2 hours) across the arrester terminals without a discharge. Leakage current is extremely low and has capacitive nature, due to ground capacitance. Point *2* corresponds to V_r – the rated voltage of a metal-oxide arrester characterizes the capability of the arrester to deal with temporary overvoltage (TOV) in the system. The standards stipulate a time period of 10 seconds [9]. Some manufacturers permit a time period of 100 seconds. The resistive component of leakage current under these conditions is about 300 μA [10]. Point *3* corresponds to V_{ref} - the reference voltage. It is the lowest peak value independent of polarity of power-frequency voltage, divided by the square root of 2, required to produce a resistive component of current equal to the reference current of the arrester or arrester element. The reference voltage of a multiunit arrester is the sum of the reference voltages of the series units. The voltage level shall be specified by the manufacturer. Reference current (I_{ref}) is the peak value of the resistive component of a power-frequency current high enough to make the effects of stray capacitance of the arrester negligible. This current level shall be specified by the manufacturer. Depending on the arrester design, the I_{ref} will typically be in the range of 0.4–10 mA [8]. At point *4* surge arrester conduct the current 2,5 – 20 kA or more.



Surge arrester V-I characteristic curves can be divided on three main regions [11]. The pre-breakdown region or the leakage current region is where an arrester is not in severe conduction mode and there are only microamperes flowing through the semiconductor. This area of the V-I curve accounts for the vast majority of a surge arrester's typical life and, since very little heat is typically generated, the surge arrester can operate almost indefinitely. The leakage current in this region is capacitive. The upper boundary of this zone corresponds to a voltage that slightly above V_{ref}. The breakdown region is the part of the V-I curve in which even minimal voltage increases lead to a significant rise in the current. This region is characterized by presence of power frequency overvoltages of relatively long duration (from a few cycles to seconds). These overvoltages usually occur on the healthy phases of a system during an earth-fault involving one or more phases. Other overvoltage sources are load-rejection, energization of unloaded lines, ferroresonance, etc. The current in the breakdown region is predominately resistive. High current region is the area of currents greater than about 100 A. The lower end of this region is where switching surges are found. The higher current region surge arrester performs its surge clamping function. The conductivity interval of surge arrester in this region is milliseconds down to microseconds. Moreover, the higher is the current, the shorter is the surge length. Also, in this region the zinc oxide grains are controlling the resistance of the surge arrester. This is the region that gives the discharge voltage or residual voltage data found in most specification charts for arresters. The current in the higher current region is predominately capacitive [8].

Model parameters adjustment. As already was noted, V-I curve is a critical feature of the surge arrester. But equipment manufacturers don't always provide the full range V-I curve in their buyer guides and catalogs. Information that allows matching a certain current value to voltage value is the maximum residual voltage with current wave. Residual voltage (V_{res}) is the peak value of the impulse voltage that appears between the terminals of an arrester during the flow of discharge current. Usually, two types of discharge current are presented in catalogs. There are switching current impulse and lightning current impulse**.** The switching current impulse is the peak magnitude of discharge current having a recommended standard impulse shape, a virtual front time greater than 30 μs but less than 100 μs and a virtual time to half value on the tail of roughly twice the virtual front time [3]. The current amplitudes lie between 500 A and 3 kA for high voltage station class arresters, and roughly reproduce the load of an arrester caused by overvoltage due to circuit breaker operation. The lightning current impulse is the peak magnitude of discharge current having a recommended standard impulse shape, a virtual front time greater than 7 μs but less than 9 μs and from 18 to 22 μs for time to half-value on the tail. The current amplitudes lie between 5 kA and 40 kA for high voltage station class arresters. The duration of the standard switching and lightning impulses respectively are 30/60 and 8/20 μs [9, 12]. Residual voltage of 800 kV surge arresters for the impulses of different amplitudes is shown in the table 1 [13, 14]. As we see, the residual voltage of the arrester with the same rated voltage V_r of both manufacturers are different. This can be explained by the difference in characteristics of the ZnO blocks from which they are assembled. Therefore, we need to build V-I curve for surge arresters of each manufacturer.

Table 1

Rated voltage V_r, kV rms	MCOV V_c, kV rms	Maximum residual voltage with current wave, kV manufacturer's data							
		30/60 μs				8/20 μs			
		0,5, kA	1, kA	2, kA	3, kA	5, kA	10, kA	20, kA	40, kA
ABB Exlim T									
588	470	-	1134	1167	1189	1247	1299	1402	1525
612	490	-	1180	1214	1237	1298	1351	1459	1587
624	499	-	1203	1238	1261	1323	1378	1488	1618
Siemens 3EQ3									
588	470	1098	1131	1164	-	1250	1323	1442	1574
612	490	1143	1177	1212	-	1301	1377	1501	1639
624	499	1165	1200	1236	-	1327	1404	1530	1671

The Matlab default parameters k and α of each segment are: k_1=0,955, α_1=50, k_2=1,0, α_2=25, k_3=0,9915, α_3=16,5 [4]. The parameters of V-I curve for each segment will be determined by the least squares method. First of all, find the transition currents. The transition currents from segment *1* to segment *2* and from segment *2* to segment *3* are equal to

$$i_{12} = P_1\left(P_1 / P_2\right)^{\frac{\alpha_1}{\alpha_2-\alpha_1}},\ i_{23} = P_2\left(P_2 / P_3\right)^{\frac{\alpha_2}{\alpha_3-\alpha_2}}, \tag{3}$$

where $P_i = nI_{Base} / k_i^{\alpha_i}$, $i = 1,2,3$, n is the number of ZnO block columns.

Calculate the transition currents under default parameters. They values are i_{12}=100,04 A, i_{23}=1513,25 A. Thus, for the ABB surge arresters we preliminarily have 1 point of the V-I curve in the second segment and 6 points in the third. For the Siemens surge arresters we have 2 points in the second segment and 5 points in the third. There are no points of the V-I curve in the first segment for surge arresters of both companies.

Simulation results of residual voltage of surge arresters under default parameters presented in table 2. I=1 kA and corresponding value of V_{res} were chosen as the base point for equation (3). This led to the fact

Table 2

Rated voltage V_r, kV rms	MCOV V_c, kV rms	Maximum residual voltage with current wave, kV Matlab simulation with default parameters							
		30/60 μs				8/20 μs			
		0,5, kA	1, kA	2, kA	3, kA	5, kA	10, kA	20, kA	40, kA
ABB Exlim T									
588	470	-	1133,6	1170,93	1199,33	1235,83	1287,35	1340,97	1396,8
612	490	-	1179,57	1218,41	1247,96	1285,95	1339,56	1395,36	1453,47
624	499	-	1202,55	1242,15	1272,28	1311,02	1365,66	1422,54	1481,79
Siemens 3EQ3									
588	470	1099,22	1130,61	1167,84	-	1232,56	1283,95	1337,42	1393,11
612	490	1143,88	1176,57	1215,32	-	1282,68	1336,16	1391,82	1449,78
624	499	1166,21	1199,55	1239,06	-	1307,74	1362,27	1419,02	1478,11

that *Vres* obtained as the results of the simulation for 1 kA impulse will very exactly match the value from the manufacturer catalog. The difference is about 0.4 kV. The difference under the current impulse of 0.5 kA for Siemens surge arresters is 0,88 – 1,22 kV or 0,08-0,122%. This can be explained by the fact that the current value of 0.5 kA is located in the second segment of the V-I curve, which is enough accurately represented by the default parameters *k* and *α* Further, with increasing current, the difference between the simulation results and the manufacturer's data increases. Its absolute value for 40 kA impulse reaches 136,2 kV for ABB surge arresters and 192,9 kV for Siemens surge arresters or about 8,4% and 11,5%. Therefore, the default parameters *k* and *α* of the third segment of the V-I curve are subject to adjustment.

Using the least squares method, we find the parameters *k* and *α* for the third V-I curve segment. Then we calculate again the transition current values. We repeat this procedure several times to make sure that the transition currents do not change significantly. If significant changes occur, then we find the residual voltages with current wave 30/60 and 8/20 μs for the two pairs of *k* and *α* and choose the best. As a result, the following values were obtained for the third segment of the V-I curve: k_3=0,9542 and α_3=11,2992 for ABB Exlim T models; k_3=0,9458 and α_3=9,9384 for Siemens 3EQ3 models. Unfortunately, the insufficient number of points in the second segment and their absence in the first do not allow adjusting all V-I curve parameter.

The results of simulation with adjusted *k* and *α* are presented in table 3. The residual voltage of the ABB surge arresters, except 10 kA impulse, has become much close to the manufacturer's values. The amplitude of residual voltage deviation at 10 kA impulse increased from 11,5-12,3 kV to 34,5-37 kV. But at 40 kA impulse, the deviation decreased by more than 10 times and became less than 13 kV. The maximal relative value of deviation is less than 2,7 %.

The absolute residual voltage deviation of Siemens surge arrester decreased in all points. The maximal absolute value of deviation doesn't exceed 29 kV and relative – 1,82 %.

Table 3

Rated voltage V_r, kV rms	MCOV V_c, kV rms	Maximum residual voltage with current wave, kV Matlab simulation with adjusted parameters							
		30/60 μs				8/20 μs			
		0,5, kA	1, kA	2, kA	3, kA	5, kA	10, kA	20, kA	40, kA
ABB Exlim T									
588	470	-	1133,6	1165,73	1195,61	1252,3	1333,9	1420,73	1513,18
612	490	-	1179,57	1213,01	1244,09	1303,09	1388	1478,36	1574,57
624	499	-	1202,55	1236,65	1268,33	1328,48	1415,05	1507,17	1605,25
Siemens 3EQ3									
588	470	1099,21	1130,61	1162,65	-	1256,81	1347,17	1443,96	1547,65
612	490	1143,88	1176,57	1209,93	-	1307,92	1401,96	1502,68	1610,6
624	499	1166,21	1199,54	1233,56	-	1333,47	1429,35	1532,46	1642,06

Conclusion. The studies in this article showed that transient simulation using the default Matlab V-I curve parameters of a surge arrester can lead to the deviation in determining the residual voltage up to 11%. As the current in the region of switching and lightning impulses increases, the deviation between the simulation results of residual voltage and manufacturer's data also increases. To adjust the V-I curve parameters of the surge arrester, it is proposed to use the least squares method based on manufacturer's catalog data. The calculations of the residual voltage showed, that using the adjusted V-I curve allows to reduce the maximum relative deviation by 3-6,5 times and absolute deviation by 120-160 kV. Adjustment of the model parameters provide more accurate results of the transient overvoltage simulation and will allow to more accurately choose a surge arrester for effective overvoltage protection.

The article was prepared on the basis of research within the scientific project No.: III-32-19 "Development of methods and models for the analysis of electromagnetic transient processes in order to prevent overvoltage". Program code of classification of expenses «6541030».

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УДК 621.311

УТОЧНЕННЯ ПАРАМЕТРІВ MATLAB МОДЕЛІ ОБМЕЖУВАЧА ПЕРЕНАРУГИ

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Запропоновано метод уточнення параметрів моделі обмежувача перенапруги з бібліотеки Matlab Simscape. Він оснований на побудові нелінійної вольт-амперної характеристики шляхом апроксимації залишкової напруги і імпульсу струму функцією заданого виду за даними каталогів виробників. Отримані параметри експоненціальної функції перевіряються шляхом моделювання перехідного процесу під впливом стандартних імпульсів струму на обмежувач перенапруги. Бібл. 14, рис. 1, табл. 3.

Ключові слова: обмежувач перенапруги з оксиду цинку, параметри математичної моделі, залишкова напруга, імпульс струму.

УДК 621.311

УТОЧНЕНИЕ ПАРАМЕТРОВ MATLAB МОДЕЛИ ОГРАНИЧИТЕЛЯ ПЕРЕНАПРЯЖЕНИЯ

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В статье предложен метод уточнения параметров модели ограничителя перенапряжений из библиотеки Matlab Simscape. Он основан на построении вольт-амперной характеристики путем аппроксимации остаточного напряжения и импульса тока функцией заданного вида по данным каталогов производителей. Полученные параметры экспоненциальной функции проверяются путем моделирования переходного процесса под воздействием стандартных импульсов тока на ограничитель напряжения. Библ. 14, рис. 1, табл. 3.

Ключевые слова: ограничитель перенапряжения из оксида цинка, параметры математической модели, остаточное напряжение, импульс тока.

Надійшла 07.02.2020
Остаточний варіант 30.06.2020