UDC 621.316.93
DOI: 10.15587/2312-8372.2017.117836

Brzhezitsky V.,
Trotsenko Ye.,
Haran Ya.

ANALYSIS AND COMPARISON OF METAL-OXIDE SURGE ARRESTER MODELS

Проведено порівняння різних моделей металлоксидних обмежувачів перенапруг нелінійних. Пропонується досліджувати моделі обмежувачів перенапруг нелінійних як при впливі імпульсів струму, так і імпульсів напруги різної амплітуди і форми. При остаточному виборі обмежувача перенапруг нелінійного рекомендується використовувати модель, яка дає максимальні значення залишкової напруги при впливі на модель тестових імпульсів напруги.

Ключові слова: *моделі обмежувачів перенапруг нелінійних, імпульс струму, імпульс напруги, вольт-амперна характеристика.*

1. Introduction

Surge arresters are widely used to protect the insulation of equipment at stations and substations from overvoltage waves that arrive from transmission lines. Lightning overvoltage waves arise and propagated along the wires of overhead transmission lines as a result of lightning strokes. Various analog and digital circuit simulation programs are used to compute the magnitude and waveform of overvoltage to which the electrical insulation of substations is subjected. Various equivalent circuits and models of manufactured metal-oxide surge arresters are used in computations. Performance of surge arresters during overvoltage limitation depends on a number of factors, including the magnitude and duration of the oncoming voltage impulse. Proposed equivalent circuit of surge arrester should as closely as possible reproduce the protective performance of real apparatus. Therefore, prior to simulation of complex substation schemes, simulation of a particular surge arrester model is carried out. During such testing, it is advisable to use the surge arrester model in the scheme that most closely matches the operating conditions of a real surge arrester.

2. The object of research and its technological audit

The objects of the research are: full [1] and simplified [2] dynamic models of surge arresters, as well as the model of surge arrester in the form of a nonlinear resistor. For the simulation of the voltage-current characteristics, in the latter case the approximation [3] was used, describing by one expression both switching and lightning surge domain. These known models [1, 2] and model [3] are chosen to demonstrate principles that can later be applied to other models of surge arresters.

At the present time, the following approach, traditional to a certain extent, is applied for the study of surge arrester models. The surge arrester model is connected in series with a current source of a given waveform and amplitude. Then, the residual voltage is computed on the surge arrester model. The simulation results are compared with the corresponding passport values that the manufacturer indicates and a conclusion is made about the applicability of this model.

It should be noted that such approach does not fully match the use of real surge arresters in operation. In practice, the surge arrester is connected in parallel with the equipment to be protected. As a result of lightning activity, surge arresters are exposed to impulse voltage waves of various origins. The use of voltage impulses in comparing the models of metal-oxide surge arresters has not been studied sufficiently yet.

3. The aim and objectives of research

The aim of the article is development of recommendations for improving the method of comparing metal-oxide surge arrester models. To achieve this aim, the following tasks are formulated:

1. Comparison of the multivariate analysis results when lightning current impulses are applied to the surge arrester models.
2. Comparison of the multivariate analysis results when lightning voltage impulses are applied to the surge arrester models.
3. Error analysis and the formulation of the final recommendations.

4. Research of existing solutions of the problem

The analysis of papers [1, 2, 4–10] published in different years shows that basically when comparing different models of metal-oxide surge arresters, the above approach with a series connection of the current source and the surge arrester model is used. In most cases, the residual voltage is determined when model is exposed to lightning current impulses, as well as a steep current impulse. Thus, in [2, 5, 7–10], lightning current impulses and steep current impulses were used. In [1, 4, 6], in addition, switching current impulses were used to determine the residual voltage. In [6], a simplified simulation of the protection circuit for a power transformer using surge arrester was also performed. The graphs of the transient process on the insulation of the transformer and on the surge arrester subjected to a switching current impulse are given.

Triangular, that is, piecewise linear, voltage impulse was used in [10] to quick determining the maximum of the residual voltage.

In [11], the results of a comparison of two models subjected to a lightning voltage impulse (full and chopped) and a switching voltage impulse are presented. However, the effect of several voltage impulses of different amplitudes was not studied.

5. Methods of research

To achieve objectives that were set such research method were applied: equivalent generator method, multivariate analysis, as well as circuit simulation on a personal computer. The main material of this research are full and simplified dynamic models of surge arresters, as well as the model of surge arrester in the form of a nonlinear resistor.

6. Research results

Circuits intended for determining the residual voltage of surge arrester when current impulses are applied to it are shown in Fig. 1.

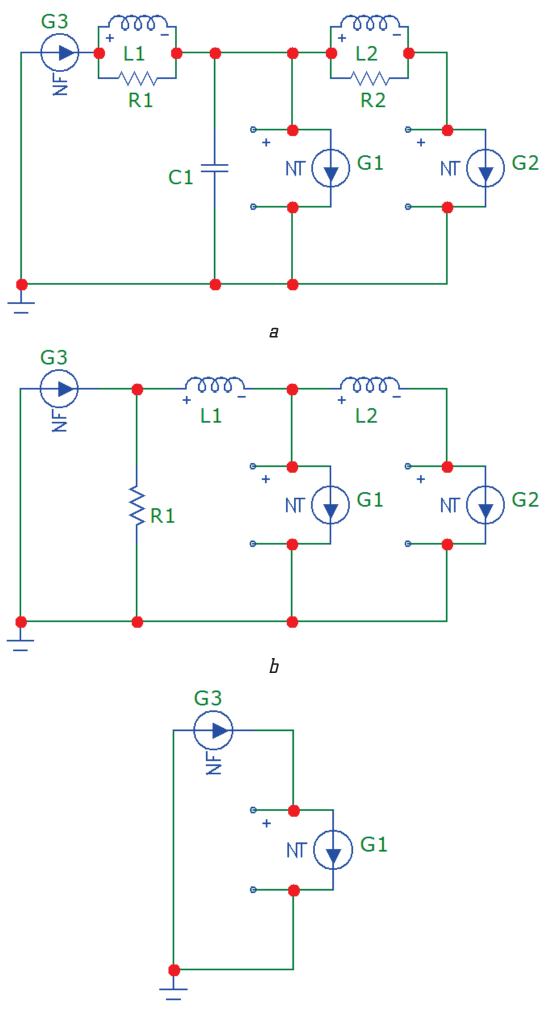

Fig. 1. Impact of current impulses on the surge arrester model when using: *a* – full dynamic model [1]; *b* – simplified dynamic model [2]; *c* – nonlinear resistor, with a voltage-current characteristic according to [3]

In Fig. 1, R_1, R_2, L_1, L_2 and C_1 – linear, G_1 and G_2 – nonlinear elements of surge arrester model. The procedures for determining the parameters of these models differ significantly and are described, correspondingly, in [1–3].

Simulation of the surge arrester is performed with a help of the Micro-Cap Evaluation/Student Version [12]. All the nonlinear elements in the schemes in Fig. 1 are simulated with the help of voltage controlled current sources G_1 and G_2 (NTIofV), in accordance with the procedure described in [13, 14].

Above schemes (Fig. 1) corresponds to the traditional approach to the comparison of surge arrester models: series connection of surge arrester model and a current source of a given shape and amplitude, followed by voltage drop measurement between the surge arrester terminals.

A typical surge arrester with the following parameters was chosen for the study: the rated voltage is 108.0 kV (root-mean-square value): the residual voltage at a nominal discharge current with 10.0 kA amplitude and 8/20 µs waveform is 285 kV (peak value).

In accordance with the calculation procedure [1], for the model in Fig. 1, *a*: $L_1=0.219$ µs, $L_2=8.210$ µs, $R_1=109.47$ Ω, $R_2=71.158$ Ω, $C_1=94.346$ pF. Similarly, in accordance with the calculation procedure [2], it was found that for the model in Fig. 1, *b*: $L_1=0.947$ µs, $L_2=2.842$ µs, $R_1=1000$ MΩ.

The voltage-current characteristic of a nonlinear resistor in the model in Fig. 1, *c* in the whole range of both switching and lightning current impulses accordingly to [3] was given by the expression (1).

$$U(I)=a+b\cdot\left(\log_{10}(I)\right)^{k}. \qquad (1)$$

According to [3], the values of *a*, *b* and *k* parameters are specific for each certain surge arrester and must be determined from the system of nonlinear equations (2).

$$\begin{cases} a\cdot m_1+b\cdot\sum_{i=1}^{m_1}\left(\log_{10}(I_i)\right)^k=\sum_{i=1}^{m_1}U_i, \\ a\cdot(m_2-m_1)+b\cdot\sum_{i=m_1+1}^{m_2}\left(\log_{10}(I_i)\right)^k=\sum_{i=m_1+1}^{m_2}U_i, \\ a\cdot(n-m_2)+b\cdot\sum_{i=m_2+1}^{n}\left(\log_{10}(I_i)\right)^k=\sum_{i=m_2+1}^{n}U_i, \end{cases} \qquad (2)$$

where I_i, U_i – values of currents and voltages from the catalog of surge arresters; n – total number of pairs of «current-voltage» values; m_1, m_2 – the boundaries of intermediate intervals.

Having solved the system of equations (2), it was found that for this surge arrester, its voltage-current characteristic can be described by the expression:

$$U(I)=183.320782+1.349608\cdot\left(\log_{10}(I)\right)^{3.129625}, \qquad (3)$$

wherein the current I is expressed in amperes, and the voltage U is in kilovolts.

A comparison of these three surge arrester models was carried out using a multivariate analysis (Stepping). In order to compute and compare the residual voltage in all models, the amplitude of the lightning current impulse in the circuits in Fig. 1 varied from 2.0 to 20.0 kA (Fig. 2).

Accordingly, three sets of residual voltage curves were obtained, shown in Fig. 3–5.

ISSN 2226-3780

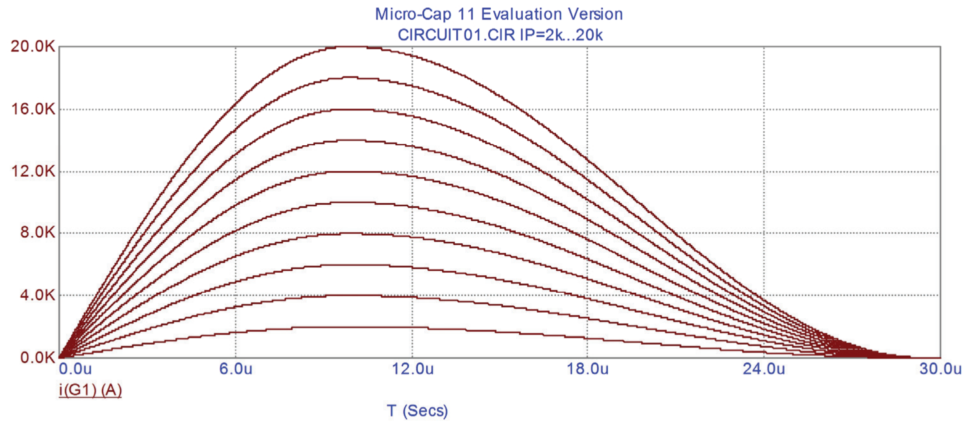

Fig. 2. Set of currents with 8/20 μs waveform, flowing through all surge arrester models

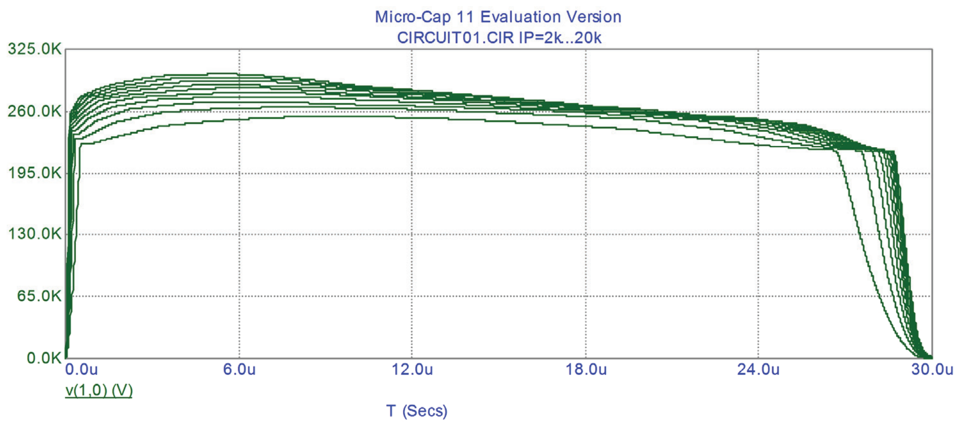

Fig. 3. Set of residual voltage curves obtained in the circuit in Fig. 1, *a*

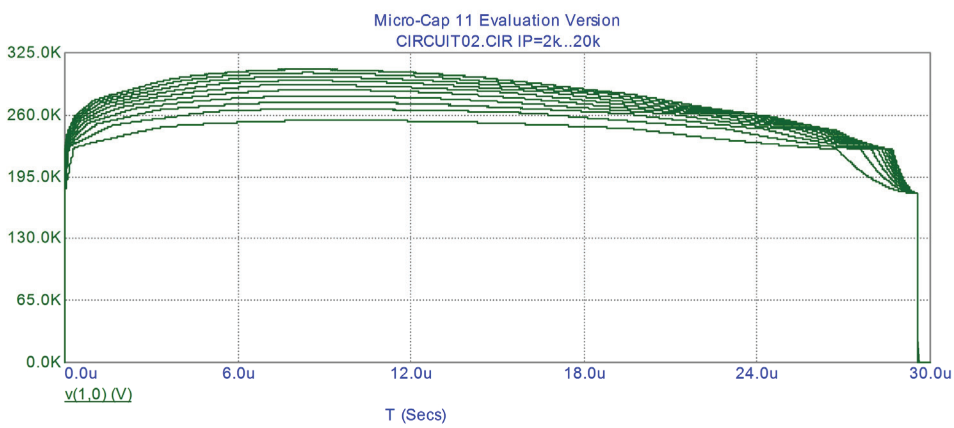

Fig. 4. Set of residual voltage curves obtained in the circuit in Fig. 1, *b*

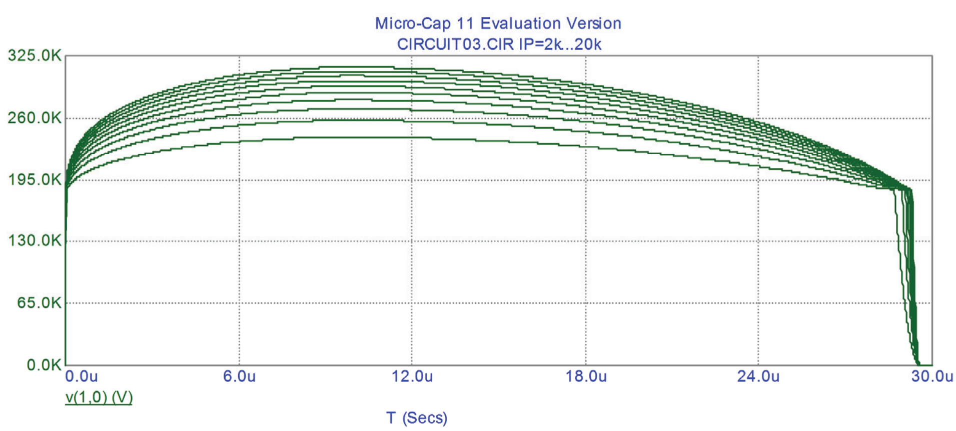

Fig. 5. Set of residual voltage curves obtained in the circuit in Fig. 1, *c*

In order to represent the current impulses with the 8/20 µs waveform, expression (4) was used in accordance with [15].

$$i_{8/20}(t)=\begin{cases} I_p\cdot\sin(\omega t),\ 0\le t\le\dfrac{\pi}{2\omega}, \\ I_p\cdot\dfrac{\sin(\omega t)+1}{2},\ \dfrac{\pi}{2\omega}\le t\le\dfrac{3\pi}{2\omega}, \\ 0,\ \dfrac{3\pi}{2\omega}\le t<\infty, \end{cases} \quad (4)$$

where I_p – peak value, A; $\omega=159312.827162$ rad/s.

A comparison of the residual voltage curves given in Fig. 3–5, showed the following. The results obtained with the model [2] do not differ from the results obtained with the model [1] by more than 2.89 %. The results obtained with the model [3] do not differ from the results obtained with the model [1] by more than 5.74 %. The results obtained with the model [3] do not differ from the results obtained with the model [2] by more than 5.67 %.

Thus, both dynamic models [1] and [2] predict almost the same maximum value of the residual voltage. On the other hand, there is a marked difference in the shape of the residual voltage curves, which is increasingly manifested with an increase in the amplitude of the discharge current flowing through the surge arresters. In this case, the use of the model [1] gives somewhat lower values of the residual voltage than the use of the model [2]. In this case, in comparison with the models [1] and [2], in the domain of low currents (up to about 4.0 kA), the use of the model [3] gives somewhat underestimated values, while in the domain of high currents it is somewhat too high.

Circuits for computing the voltage drop between the surge arrester terminals when the voltage impulses are applied to it are shown in Fig. 6. These circuits are compiled in accordance with the equivalent generator theorem (also known as the Thevenin's theorem) [16, 17]. According to Thevenin's theorem, any linear electrical circuit consisting of several voltage sources and resistors with respect to any two points to which a certain load is connected, can be replaced by an equivalent circuit with one voltage source and one resistor that are connected in series and connected to this load.

The schemes in Fig. 6 correspond to the case when two lines of infinite length are connected to the surge arrester. At the same time, an overvoltage wave with 1.2/50 µs waveform propagates along the one of these lines to the surge arrester. In the schemes in Fig. 6 branch with surge arrester is left unchanged, and the rest of the circuit in relation to it is replaced by an equivalent voltage source and an equivalent resistor. The surge arrester considered in this work is intended for 110 kV networks. Accordingly, for 110 kV networks, the line impedance is 450 Ω.

In accordance with Thevenin's theorem, the equivalent voltage source in Fig. 6 is given by:

$$E_1=\frac{2\cdot 450}{450+450}\cdot 1.044\cdot U_m\cdot\left(e^{-1.400\cdot 10^4\cdot t}-e^{-1.917\cdot 10^6\cdot t}\right)=$$

$$=1.044\cdot U_m\cdot\left(e^{-1.400\cdot 10^4\cdot t}-e^{-1.917\cdot 10^6\cdot t}\right),$$

where U_m – peak value of overvoltage wave, V.

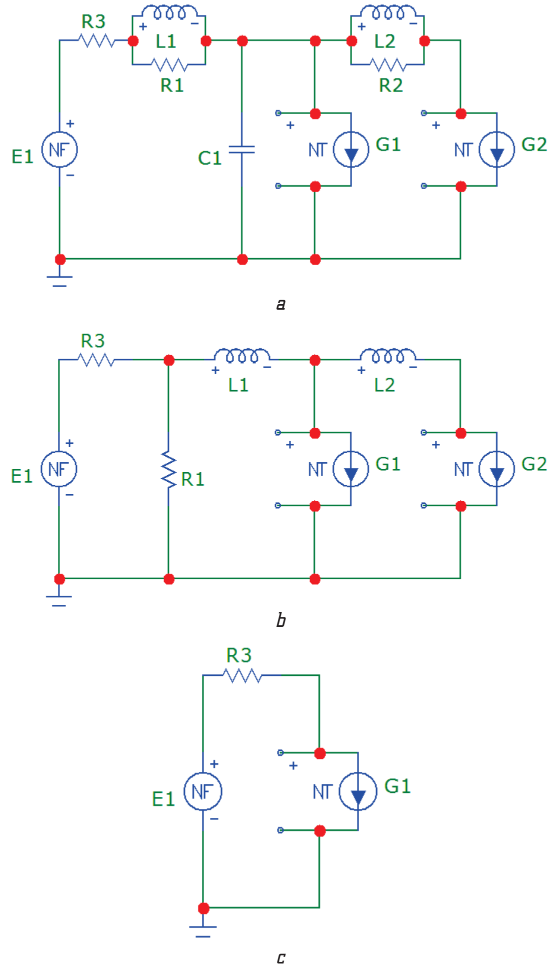

Fig. 6. Impact of voltage impulses on the surge arrester model when using: *a* – full dynamic model [1]; *b* – simplified dynamic model [2]; *c* – nonlinear resistor, with a voltage-current characteristic according to [3]

In its turn, the resistance of the equivalent resistor in Fig. 6 is given by:

$$R_3=\frac{450\cdot 450}{450+450}=225\ \Omega.$$

Comparison of the three surge arrester models is similarly carried out using a multivariate analysis (Stepping). In order to compute and compare the voltage drop between the terminals of both models, the amplitude of the voltage source in the circuits in Fig. 6 varied from 400.0 to 1600.0 kV (Fig. 7).

Accordingly, three sets of voltage drop curves were obtained between the surge arrester terminals, shown in Fig. 8–10. These curves represent a refracted voltage wave that will propagate along the second line after passing through the surge arrester.

A comparison of the voltage drop curves given in Fig. 8–10, showed the following. The results obtained with the model [2] do not differ from the results obtained with the model [1] by more than 4.53 %. The results obtained with the model [3] do not differ from the results obtained with the model [1] by more than 9.41 %. The results obtained with the model [3] do not differ from the results obtained with the model [2] by more than 7.85 %.

ISSN 2226-3780

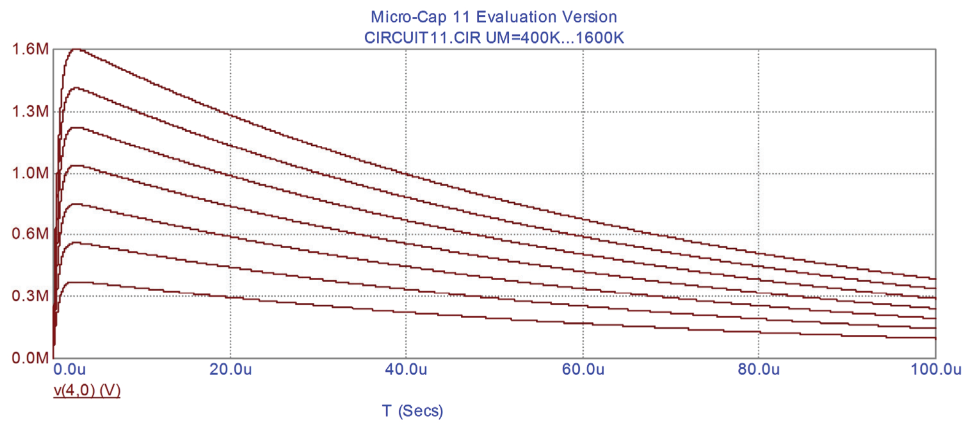

Fig. 7. Set of voltage impulses with 1.2/50 μs waveform, applied to all surge arrester models

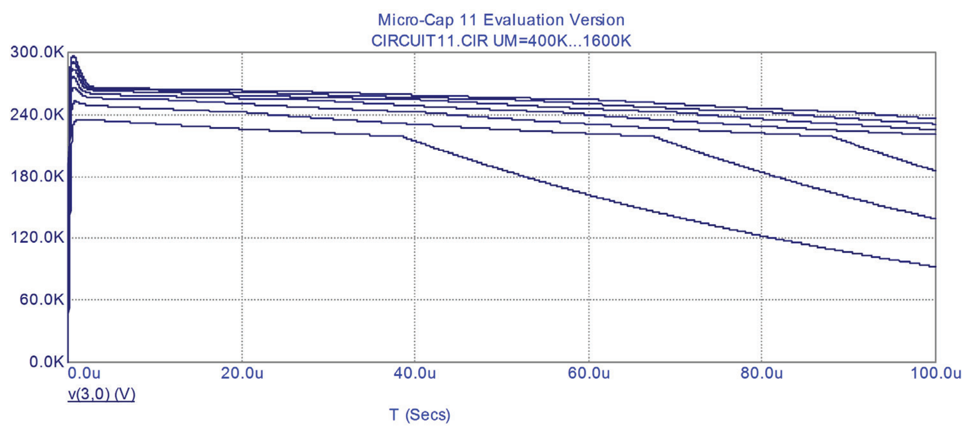

Fig. 8. Set of voltage drop curves between the surge arrester terminals, obtained in the circuit in Fig. 6, *a*

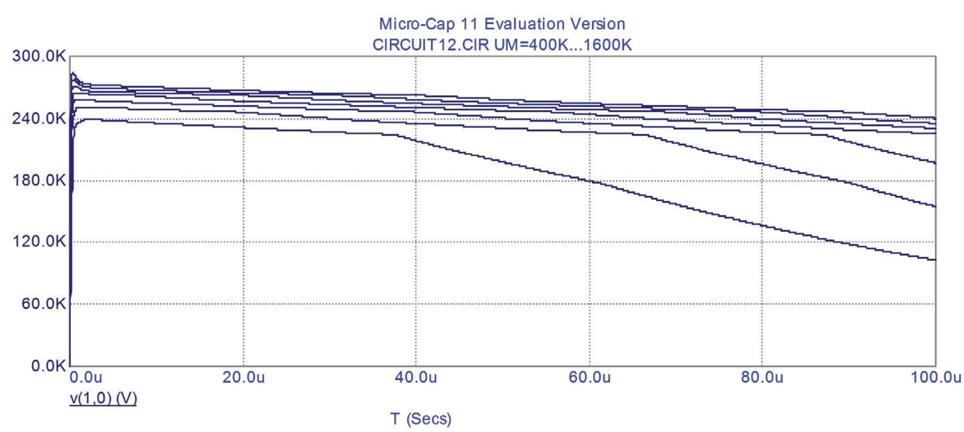

Fig. 9. Set of voltage drop curves between the surge arrester terminals, obtained in the circuit in Fig. 6, *b*

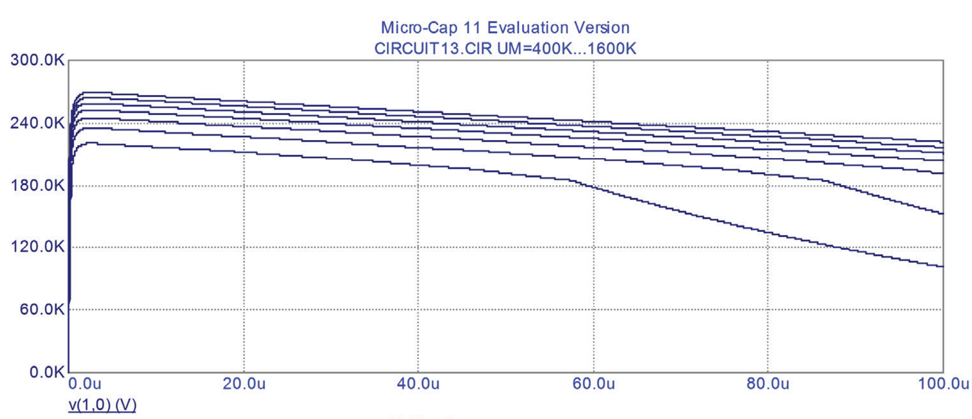

Fig. 10. Set of voltage drop curves between the surge arrester terminals, obtained in the circuit in Fig. 6, *c*

Thus, in comparison with the first experiment (Fig. 1), in the second experiment (Fig. 6) the difference in the values of the residual voltage increased. However, it is noteworthy that even when modeling a surge arrester in the form of a nonlinear resistor, which is a strong simplification, the results do not go beyond the limits of engineering accuracy. This is achieved by using the expression (1) to approximate the voltage-current characteristic of surge arresters. It is known that in general form the voltage-current characteristic of surge arrester [17] is given by the expression (5):

$$U(I) = K \cdot I^{\alpha}, \qquad (5)$$

where α is the coefficient of nonlinearity of the metal-oxide varistor disk; K is a constant, which depends on the material and dimensions of the metal-oxide varistor disk.

Recall that in the typical voltage-current characteristic of metal-oxide varistor disks for the entire range of current values at normal system voltage and at overvoltage, three regions are identified, on which the coefficient α takes different values [17]. The advantage of formula (1) in comparison with formula (5) is that in the domains of switching and lightning overvoltage the voltage-current characteristic can be described not by two, but by one expression.

Regarding the surges on front in Fig. 8, 9 it should be noted that in reality they will be smoothened. This is explained by the fact that when the surge wave propagates along the line, the wave front is increased (smoothed) by the corona on the wires, losses in the earth and in the wires themselves.

In conclusion, it can be noted that when making final choice of a particular surge arrester model, it is preferable, because of the need for a certain safety factor, to choose model which gives largest residual voltage values in schemes similar to Fig. 6.

7. SWOT analysis of research results

Strengths. The strengths of this research are:

– use of several models that represent a variety of approaches to the modeling of surge arresters;

– in contrast to other studies, the proposed approach to comparison of surge arrester models most closely corresponds to the way of using real surge arresters in operation.

Weaknesses. The weak side of this study is that the proposed procedure for comparing surge arrester models is time-consuming.

Opportunities. The additional opportunities that this research provides include:

– possibility to use other non-standard voltage impulses (including digitized oscillograms of real overvoltage at substations) when comparing different models of surge arresters;

– possibility of further improving the approximation accuracy of the current-voltage characteristic of a surge arrester.

Threats. Full and simplified dynamic model, as well as a model in the form of separate nonlinear resistor, do not take into account the thermal regime of the surge arrester and, accordingly, the heating of its metal-oxide varistor disks when the overvoltage is limited. For such cases, it is also necessary to use the thermal model of a surge arrester, for example, according to [18]. Studies [19] show that when estimating the energy dissipated in surge arresters during overvoltage limitation, both dynamic (frequency-dependent) models and a nonlinear resistor (albeit to a lesser extent) give strongly underestimated results, especially for current impulses with a steep front. Underestimated values are dangerous in that they can lead to a misinterpretation of the simulation results. Therefore, the problem of calculating overvoltage magnitude and calculating the energy dissipated requires different approaches.

8. Conclusions

1. A multivariate analysis of various surge arrester models subjected to the lightning current impulses was carried out. The residual voltage, which arises in this case on the surge arresters, was computed. It was found that results obtained with the model [2] do not differ from the results obtained with the model [1] by more than 2.89 %. The results obtained with the model [3] do not differ from the results obtained with the model [1] by more than 5.74 %. The results obtained with the model [3] do not differ from the results obtained with the model [2] by more than 5.67 %.

2. A multivariate analysis of the same surge arrester models subjected to the lightning voltage impulses was carried out. The residual voltage, which arises in this case between the terminals of surge arresters, was computed. It was found that results obtained with the model [2] do not differ from the results obtained with the model [1] by more than 4.53 %. The results obtained with the model [3] do not differ from the results obtained with the model [1] by more than 9.41 %. The results obtained with the model [3] do not differ from the results obtained with the model [2] by more than 7.85 %.

3. Compared with the first approach, the schemes used in the second approach more closely matches the way in which real surge arrester is used in operation. As a result, when making final choice of a particular surge arrester model, it is preferable, because of the need for a certain safety factor, to choose model which gives largest residual voltage values when the voltage impulses are applied.

On the other hand, it has been established that even when modeling a surge arrester in the form of a nonlinear resistor, but taking into account the approximation of its voltage-current characteristic by [3], the results do not exceed the limits of engineering accuracy.

References

1. Modeling of metal oxide surge arresters [Text] // IEEE Transactions on Power Delivery. – 1992. – Vol. 7, No. 1. – P. 302–309. doi:10.1109/61.108922
2. Pinceti, P. A simplified model for zinc oxide surge arresters [Text] / P. Pinceti, M. Giannettoni // IEEE Transactions on Power Delivery. – 1999. – Vol. 14, No. 2. – P. 393–398. doi:10.1109/61.754079
3. Brzhezitsky, V. Approximation of Volt-Ampere Characteristics of Metal-Oxide Surge Arresters [Text] / V. Brzhezitsky, I. Masluchenko, Y. Trotsenko, D. Krysenko // Scientific Works of National University of Food Technologies. – 2015. – Vol. 21, No. 1. – P. 169–176.
4. Saengsuwan, T. Lightning arrester modeling using ATP-EMTP [Text] / T. Saengsuwan, W. Thipprasert // 2004 IEEE Region 10 Conference TENCON 2004. – IEEE, 2004. – P. 377–380. doi:10.1109/tencon.2004.1414786

ISSN 2226-3780

5. Peppas, G. D. Surge arresters models for fast transients [Text] / G. D. Peppas, I. A. Naxakis, C. T. Vitsas, E. C. Pyrgioti // 2012 International Conference on Lightning Protection (ICLP). – IEEE, 2012. – P. 1–6. doi:10.1109/iclp.2012.6344285
6. Li, H. J. A parameter identification technique for metal-oxide surge arrester models [Text] / H. J. Li, S. Birlasekaran, S. S. Choi // IEEE Transactions on Power Delivery. – 2002. – Vol. 17, No. 3. – P. 736–741. doi:10.1109/tpwrd.2002.1022797
7. Magro, M. C. Validation of ZnO Surge Arresters Model for Overvoltage Studies [Text] / M. C. Magro, M. Giannettoni, P. Pinceti // IEEE Transactions on Power Delivery. – 2004. – Vol. 19, No. 4. – P. 1692–1695. doi:10.1109/tpwrd.2004.832354
8. Fernandez, F. Metal-oxide surge arrester model for fast transient simulations [Text] / F. Fernandez, R. Diaz // Proceedings of 2001 International Conference on Power System Transients. – 2001. – P. 681–687.
9. Kim, I. Study of ZnO arrester model for steep front wave [Text] / I. Kim, T. Funabashi, H. Sasaki, T. Hagiwara, M. Kobayashi // IEEE Transactions on Power Delivery. – 1996. – Vol. 11, No. 2. – P. 834–841. doi:10.1109/61.489341
10. Martinez, J. A. Parameter Determination for Modeling Systems Transients – Part V: Surge Arresters IEEE PES Task Force on Data for Modeling System Transients of IEEE PES Working Group on Modeling and Analysis of System Transients Using Digital Simulation (General Systems Subcommittee) [Text] / J. A. Martinez, D. W. Durbak // IEEE Transactions on Power Delivery. – 2005. – Vol. 20, No. 3. – P. 2073–2078. doi:10.1109/tpwrd.2005.848771
11. Miguel, P. M. Comparison of Surge Arrester Models [Text] / P. M. Miguel // IEEE Transactions on Power Delivery. – 2014. – Vol. 29, No. 1. – P. 21–28. doi:10.1109/tpwrd.2013.2279835
12. Micro-Cap 11. Electronic Circuit Analysis Program. Reference Manual [Electronic resource]. – Sunnyvale, CA: Spectrum Software, 2014. – 1040 p. – Available at: \www/URL: http://www.spectrum-soft.com/down/rm11.pdf
13. Trotsenko, Y. Surge arrester modeling using Micro-Cap [Text] / Y. Trotsenko, V. Brzhezitsky, I. Masluchenko // Technology audit and production reserves. – 2016. – Vol. 6, No. 1 (32). – P. 26–30. doi:10.15587/2312-8372.2016.86137
14. Trotsenko, Y. Study of surge arrester model under influence of various current pulses [Text] / Y. Trotsenko, V. Brzhezitsky, I. Masluchenko // Technology audit and production reserves. – 2017. – Vol. 1, No. 1 (33). – P. 44–48. doi:10.15587/2312-8372.2017.92244
15. Trotsenko, Y. Analytical representation of switching current impulses for study of metal-oxide surge arrester models [Text] / Y. Trotsenko, V. Brzhezitsky, I. Masluchenko // Technology audit and production reserves. – 2017. – Vol. 5, No. 1 (37). – P. 24–29. doi:10.15587/2312-8372.2017.109662
16. Brittain, J. E. Thevenin's theorem [Text] / J. E. Brittain // IEEE Spectrum. – 1990. – Vol. 27, No. 3. – P. 42. doi:10.1109/6.48845
17. Martinez-Velasco, J. A. Power System Transients: Parameter Determination [Text] / ed. by J. A. Martinez-Velasco. – CRC Press LLC, 2009. – 644 p. doi:10.1201/9781420065305
18. Lat, M. V. Thermal Properties of Metal Oxide Surge Arresters [Text] / M. V. Lat // IEEE Transactions on Power Apparatus and Systems. – 1983. – Vol. PAS-102, No. 7. – P. 2194–2202. doi:10.1109/tpas.1983.318207
19. He, Y. Experimental validation of MOA simulation models for energy absorption estimation under different impulse currents [Text] / Y. He, Z. Fu, J. Chen // 2016 IEEE Power and Energy Society General Meeting (PESGM). – IEEE, 2016. – P. 1–5. doi:10.1109/pesgm.2016.7741791

АНАЛИЗ И СРАВНЕНИЕ МОДЕЛЕЙ МЕТАЛЛОКСИДНЫХ НЕЛИНЕЙНЫХ ОГРАНИЧИТЕЛЕЙ ПЕРЕНАПРЯЖЕНИЙ

Проведено сравнение различных моделей металлоксидных ограничителей перенапряжений нелинейных. Предлагается исследовать модели ограничителей перенапряжений нелинейных как при воздействии импульсов тока, так и импульсов напряжения различной амплитуды и формы. При окончательном выборе ограничителя перенапряжений нелинейного рекомендуется использовать модель, которая дает максимальные значения остающегося напряжения при воздействии на модель тестовых импульсов напряжения.

Ключевые слова: модели ограничителей перенапряжений нелинейных, импульс тока, импульс напряжения, вольт-амперная характеристика.

Brzhezitsky Volodymyr, *Doctor of Technical Sciences, Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: v.brzhezitsky@kpi.ua, ORCID: http://orcid.org/0000-0002-9768-7544*

Trotsenko Yevgeniy, *PhD, Associate Professor, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: y.trotsenko@kpi.ua, ORCID: http://orcid.org/0000-0001-9379-0061*

Haran Yaroslav, *Assistant, Department of High Voltage Engineering and Electrophysics, National Technical University of Ukraine «Igor Sikorsky Kyiv Polytechnic Institute», Ukraine, e-mail: y.garan@kpi.ua, ORCID: http://orcid.org/0000-0003-3242-9218*