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Simulations of lightning overvoltages in HV electric power system for various surge arresters and transmission lines models

Abstract. This paper deals with frequency-dependent surge arresters models and transmission lines models utilized for insulation coordination studies. Simulations have performed by means of EMTP/ATP software. Various frequency-dependent surge arresters models and transmission lines models have been compared in this article. Simulations of lightning transient in analyzed power system have been performed and results presented in this paper for various surge arrester and overhead line models. Influence of models application during calculations on simulation results has also been analyzed.

Streszczenie. Artykuł dotyczy modelowania zmienno-częstotliwościowych modeli ograniczników przepięć oraz modeli linii przesyłowych, stosowanych do obliczeń koordynacji izolacji przy użyciu programu symulacyjnego EMTP/ATP. W niniejszym artykule przedstawiono wyniki symulacji przepięć podczas wyładowań piorunowych w rozpatrywanej sieci elektrycznej. Obliczenia przeprowadzono z wykorzystaniem różnych modeli ograniczników przepięć oraz linii przesyłowych, w celu porównania wpływu zastosowanego modelu ograniczników przepięć i linii przesyłowych, na wyniki symulacji. (Symulacje przepięć atmosferycznych występujących w sieci elektroenergetycznej WN dla różnych modeli matematycznych ograniczników przepięć oraz linii przesyłowych).

Słowa kluczowe: modele linii przesyłowych, modele ograniczników przepięć, przepięcia atmosferyczne, symulacje w programie EMTP/ATP
Keywords: lightning overvoltages, simulations in EMTP/ATP program, surge arresters models, transmission lines models

Introduction

Lightning overvoltages occurring in an electrical power systems are very dangerous phenomenon, which may cause damages of insulation systems in electrical devices installed in the electrical network. For this reason, from insulation coordination viewpoint limitation of overvoltages values occurring during lightning strokes is very important to increase supply reliability in electrical network. For this purpose, special devices such as Metal Oxide Surge Arresters (MOSA) are installed in electrical power networks for protection against overvoltages. Estimation of overvoltages values occurring in power system is necessary to predict effects of lightning strokes. However, because of lightning strokes randomness and inability to precise measurement of lightning overvoltages in real power system, calculations of overvoltages in power systems during transient states is the only method to estimate expected values of overvoltages in electrical power system. Thus, in order to analyze and calculate lightning transient states in power networks, dedicated simulations are necessary. For this purpose, mathematical models of power system components developed in simulation software are needed. However, because of variety of mathematical models, different simulation results can be obtained from calculations in depends on mathematical models used to computations. Therefore, research on various mathematical models have been presented in this paper.

This paper deals with frequency-dependent surge arresters models and transmission lines models utilized for overvoltages studies by means of EMTP/ATP simulation software. Various frequency-dependent surge arresters models (IEEE Working Group 3.4.11, Pinceti and Giannettoni, Fernandez and Diaz models) have been presented in this article. Moreover, simulations results for various transmission line models (PI model, frequency-dependent JMarti model, as well as JMarti model including dynamic tower footing resistance) have been also presented. Simulations of lightning transient in analyzed power system have been performed by EMTP/ATP program for various surge arrester and overhead line models to compare influence of models application on simulation results analysis.

Lightning strokes in electrical overhead lines

Lightning strokes occurring in power overhead lines can be identified as direct to phase wire or indirect to shielding wire or tower construction [1]. Both situations of lightning strokes occurring in power overhead lines have been presented in figure 1.
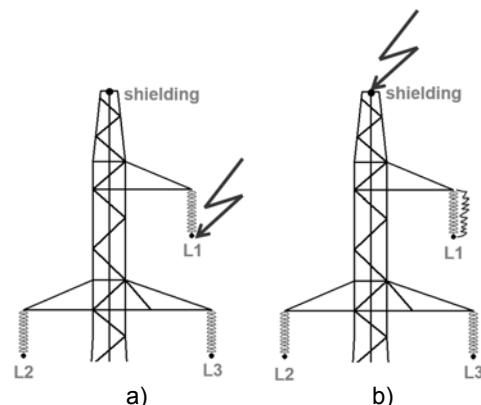

Fig.1. Typical lightning strokes situations occurring in power overhead lines: a – lightning strikes to phase wire (direct stroke situation); b – lightning strikes to tower or shielding wire (backflash situation, electric arc burns across isolator)

Way of lightning stroke occurrence to overhead line (direct, or indirect) can be estimated during insulation coordination studies base on probability (it depends inter alia on geometry of towers and peak value of lightning current stroke). In case of indirect lightning stroke in overhead lines, part of lightning current flows to the ground through tower constructions and shielding wires. However, part of lightning current can also get into phase wire through insulator as well. In this situation, electric arc burns across insulator (see figure 1b, so-called *backflash*) and voltage in power network increases over nominal value. Amount of lightning current flowing to phase wire depends on many parameters, such as peak lightning current, value of tower footing resistance or length of insulator.

For insulation coordination study, both situations of lightning stroke to overhead line should be taken into

consideration. Depending of mathematical models of power systems components applied for analysis, simulation results obtained from calculations can give various simulations results.

Surge arresters frequency-dependent models

Circuit diagrams of Metal Oxide Surge Arresters (MOSA) frequency-dependent models used to perform lightning simulations presented in this paper have been showed in figure 2.
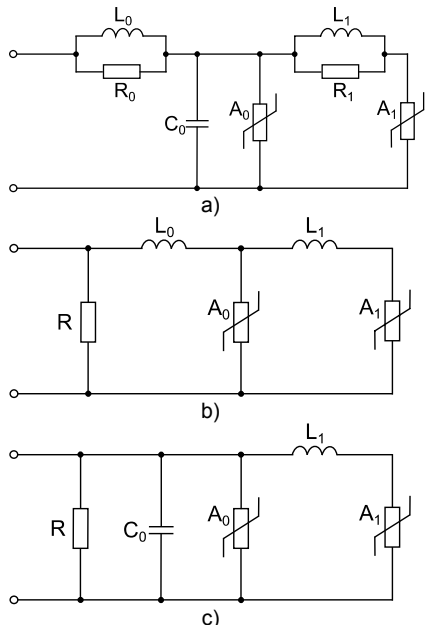

Fig.2. Surge arresters models used to lightning simulations: a) The IEEE Working Group 3.4.11 model [2]; b) The Pinceti and Giannettoni model [3]; c) The Fernandez and Diaz model [4]

All MOSA models presented in figure 2 contain linear components RLC and two non-linear I-V characteristics represented by non-linear elements A_0 and A_1 connected in parallel.

In IEEE Working Group 3.4.11 model, nonlinear elements A_0 and A_1 are connected by R_1-L_1 filter. During slow front surges, the impedance of R_1-L_1 is negligible, what causes that elements A_0 and A_1 are connected in practice in parallel. However, for fast front surges the value of impedance of R_1-L_1 increases, what causes current distribution between elements A_0 and A_1. Because of inductance L_1 influence, current flowing through A_0 increases when the surge front decreases. Parameters of linear components are related to MOSA dimensions [2].

The Pinceti and Giannettoni model presented in figure 2b, in contrast to IEEE Working Group 3.4.11 model, does not contain capacitor C_0 (according to [3], impact of C_0 absence on model behavior is negligible). Parameters of L_0 and L_1 inductances are based on non-linear I-V characteristics provided by MOSA manufacturer. Additionally, a large resistance R has been applied in this model (about 1 MΩ) to improve behavior of numerical model [3].

The Fernandez and Diaz model presented in figure 2c is based also on frequency-dependent model developed by IEEE Working Group 3.4.11. This model consists of two non-linear elements A_0 and A_1 connected only by the inductance L_1. Capacitor C_0 and resistor R have been also implemented (R resistance value is large, similarly to the Pinceti and Giannettoni model). Characteristics for nonlinear resistors A_0 and A_1 are calculated basing on I-V MOSA characteristic provided by manufacturer, according to the following assumption: the ratio of the currents flowing

through A_0 and A_1 non-linear elements is 0.02. Value of L_1 inductance is related to MOSA characteristic, whereas capacitance C_0 is calculated basing on MOSA dimensions. The resistor R has been applied to avoid numerical oscillations during simulations [4].

Procedures of parameters calculations, as well as detailed description of MOSA models analyzed in this article have been presented in [2, 3, 4].

In order to analyze surge arresters models presented in this chapter, two types of MOSA have been taken into account: air type surge arrester and GIS dedicated surge arrester used for switchgear protection, transformers and other equipment being a part of a HV system. For this purpose, ABB PEXLIM P-Y air surge arrester, and ABB AZ32 GIS surge arrester installed in GIS substations have been chosen for analysis. Both types of MOSA have been implemented into EMTP/ATP calculations according to description presented in this article. Input data for both surge arresters types have been taken from manufacturer datasheets [5].

In order to compare differences between residual voltages obtained from simulations for MOSA models (for 20 kA nominal discharge current) and residual voltages from manufacturer catalog data, surge arresters models developed in EMTP/ATP program have been tested by means of 8/20 µs current source. Simulation results of residual voltages calculated for various MOSA models of ABB PEXLIM P-Y surge arrester have been presented in figure 3.
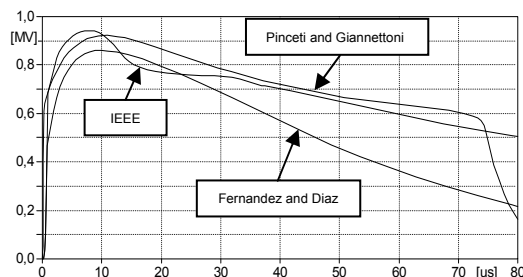

Fig.3. Calculations of residual voltage for ABB PEXLIM P-Y surge arresters models

As shown in figure 3, calculated overvoltages peak values for various models are comparable. Waveforms calculated for Pinceti and Giannettoni and Fernandez and Diaz are very similar in shape. Waveform calculated for IEEE Working Group model reaches peak value and decreases immediately after it, faster in comparison to waveforms calculated for different models. Maximum values of residual voltages for ABB PEXLIM P-Y and ABB AZ32 sure arresters have been listed in Table 1.

Table 1. Residual voltages calculated for ABB PEXLIM P-Y and for ABB AZ32 (marked bold font) surge arresters models (20 kA, 8/20 µs wave)

	Calculated data in EMTP/ATP	Data manufacturer catalog	Difference
	[kV]		[%]
The IEEE model	942 **950**		10.56 **9.95**
The Pinceti and Giannettoni model	922 **937**	852 **864**	8.22 **8.45**
The Fernandez and Diaz model	861 **874**		1.06 **1.16**

According to table 1, the largest difference between both values is observed in case IEEE Working Group for PEXLIM P-Y arrester, and it equals over 10%, while the Fernandez and Diaz model provides the highest calculations accuracy.

Transmission lines models

To evaluate influence of various transmission lines models application on simulation results in insulation coordination studies, PI model, and frequency-dependent JMarti model implemented into EMTP/ATP program have been chosen to analysis. Simulations have been performed for static tower footing resistance. For calculations with variable tower footing resistance simulation has been performed with frequency-dependent JMarti model.

Overhead line model based on PI circuit consist of linear RLC components. Typical transmission line PI model has been presented in figure 4.
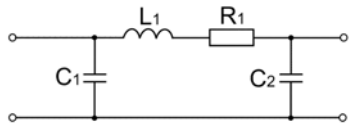

Fig.4. Overhead line PI model

PI model is a discrete approximation of the constant distributed parameter model. This equivalent circuit was used as simplified model for transient studies and can be used to model short distances of overhead lines. The main advantage of PI model is that this model is computations time step independent. However, application of PI model can cause occurring spurious oscillations by reason of lumped parameters utilization. In order to limit these oscillations, application of elements connected in parallel with the RL is useful.

More complex and precise overhead line model implemented into EMTP/ATP program, instead of linear PI model, is widely used JMarti frequency-dependent model. This transmission line model approximates the characteristic admittance and the propagation constant by rational functions, what gives improvement of simulation results accuracy. However, a constant transformation matrix in JMarti model is used to convert from mode domain to phase domain. For overhead line calculations it is not critical, however to modeling cable, it can have negative influence on simulation results accuracy. Another disadvantage of this model can be unstable behavior for very low frequency calculations.

Value of overvoltages occurring in power system during backflash situation (see fig. 1b) is related to the tower footing resistance. Because of high frequency and magnitude of lightning current the ground in the immediate vicinity of the earthing loop can be led to ionization. For this reason, value of tower footing resistance degrases during lightning transient. Therefore, to improve calculations accuracy, dynamic tower footing resistance, R_T has been implemented into overhead line model, according to dependence (1) [6].

(1)
$$R_T = \frac{R_0}{\sqrt{1 + \dfrac{I}{I_g}}}$$

where: R_0 – tower footing resistance at low current and low frequency [Ω], I – the lightning current through the footing impedance [A], I_g – the limiting current to initiate sufficient soil ionization [A].

The limiting current to initiate sufficient soil ionization from dependence (1) is determined by formula (2) [6].

(2)
$$I_g = \frac{1}{2\Pi} \cdot \frac{E_0 \cdot \rho}{R_0^2}$$

where: R_0 – tower footing resistance at low current and low frequency [Ω], E_0 – soil ionization gradient [kV/m], ρ – soil resistivity [Ω·m].

Thus, tower footing resistance has been implemented into EMTP/ATP model as nonlinear resistance, utilizing formulas (1) and (2) in MODELS block and variable resistance R(TACS) type 91.

Model of analyzed HV electrical network

General power system diagram of analyzed 400 kV electrical network used to compare various overhead line models and surge arresters models has been presented in figure 5.

Surge arresters and overhead line models have been implemented into EMTP/ATP program according to models description presented in this article. Cable sections have been modeled as LCC block basing on JMarti frequency-dependent model. Busbars of GIS substation have been modeled as surge impedance (60 Ω), with assigned length and wave propagation speed (290 m/µs).

To perform analysis, backflash situation has been considered for lightning stroke in 350 m distance from substation. For this purpose, the 8/20 µs current source has been modeled in EMTP/ATP as MODELS block connected with TACS current source basing on formula (3) [7].

(3)
$$I(t) = A \cdot I_p \cdot t^3 \cdot e^{-\left(\frac{t}{T}\right)}$$

where: A – constant (0.01243) [-]; I_p – desired peak current magnitude [kA], T – time constant (3.911 µs) [µs].

Backflash model has been implemented into EMTP/ATP program basing on Leader Progression Model [6, 8]. Its parameters are related to electric field strength needed for start of leader development [kV/m] and length of insulator installed in overhead line [m].
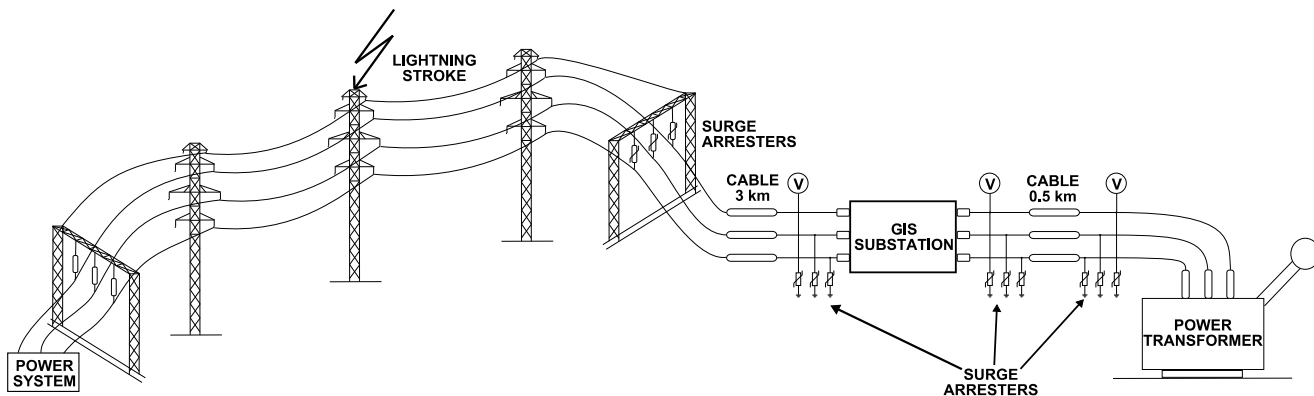

Fig.5. General analyzed network overview

Simulation results: sure arresters models

According to figure 5, voltages in analyzed power network during transient state have been calculated for three different locations in analyzed power system: at GIS entrance, cable terminal, and power transformer. Calculated waveforms for various surge arresters models have been presented in figure 6.
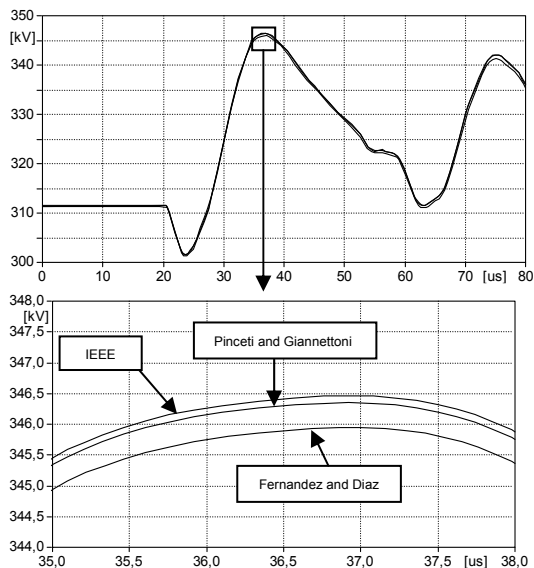

Fig.6. Voltage at power transformer terminal calculated in analyzed network for various surge arresters models

As shown in figure 6, shapes of calculated waveform are very similar. Peak values of calculated overvoltages have been listed in table 2.

Table 2. Simulation results for various surge arresters models in analyzed power system given in kV

	IEEE model	Pinceti and Giannettoni model	Fernandez and Diaz model
GIS entrance	341	341	342
Cable terminal	343	343	342
Power transformer	347	346	346

As shown in table 2, values of calculated overvoltages are very comparable. Thus, no significant differences are noticeable in simulation results performed for various surge arrester models in analysis of backflash situation in analyzed power network.

Simulation results: transmission lines models

Simulation results for various overhead line models are more diverse in comparison to simulation results for various surge arresters models. Waveforms for various overhead line models have been presented in fig. 7.
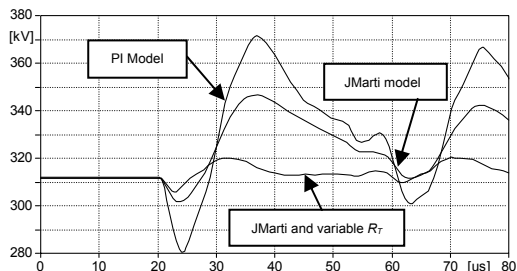

Fig.7. Voltage at power transformer terminal calculated in analyzed network for various transmission lines models

Simulation results for analysis performed for various transmission lines models have been listed in table 3.

Table 3. Simulation results for various transmission lines models in analyzed power system given in kV

	PI model	JMarti model	JMarti model including variable tower footing resistance
GIS entrance	366	343	320
Cable terminal	366	343	320
Power transformer	371	346	320

According to simulation results presented in table 3, maximum peak values in analyzed power system has been calculated for simple PI model. Overvoltages calculated for frequency-dependent JMarti model including variable tower footing resistance are the lowest.

Conclusions

In backflash situation analysis for surge arrester models, discrepancy in calculated overvoltages for analyzed power system is insignificant. Differences in simulation results are slight and reach a few kilovolts. Due to small values of overvoltages in backflash situation analysis, influence of surge arresters in negligible, however, analysis of direct stroke situation can give greater discrepancy in simulation results.

Simulation results for various transmission lines models are characterized by the highest overvoltages for PI model. For most complexity mathematical models, calculated overvoltages are lower. The smallest overvoltages has been calculated for JMarti model including variable tower footing resistance.

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