Jakub FURGAŁ

ORCID: 0000-0001-7968-6161

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Simulations of lightning overvoltages in overhead transmission lines using EMTP/ATP

Symulacje przepięć piorunowych w napowietrznych liniach przesyłowych w programie EMTP/ATP

***Abstract**: Insulation systems for overhead transmission lines and devices for power substations are subject to overvoltages of high values during lightning discharges. Lightning overvoltages in overhead lines and substations are the result of the phenomena of voltage wave propagation generated during lightning currents. For the purposes of simulation of lightning overvoltages, appropriate models of power lines and devices as well as lightning currents are used. The paper presents simulations of lightning overvoltages in the selected part of the 220 kV transmission system in the Electromagnetic Transisients Program/Alternative Transients Program (EMTP-ATP)*

***Streszczenie:** Układy izolacyjne napowietrznych linii przesyłowych i urządzeń stacji elektroenergetycznych poddawane są działaniu przepięć o dużych wartościach podczas wyładowań piorunowych. Przepięcia piorunowe w liniach napowietrznych i rozdzielniach są efektem zjawisk propagacji fal napięciowych generowanych podczas oddziaływania prądów piorunowych. Dla celów symulacji przepięć piorunowych w liniach napowietrznych stosowane są odpowiednie modele linii i urządzeń elektroenergetycznych oraz modele prądów wyładowań piorunowych. W artykule przedstawiono symulacje przepięć piorunowych w wybranym fragmencie układu przesyłowego 220 kV wykonane w programie Electromagnetic Transients Program/Alternative Transients Program (EMTP/ATP)*

Keywords: electrical power transmission systems, modeling, lightning overvoltages, simulations, EMTP/ATP
Słowa kluczowe: elektroenergetyczne układy przesyłowe, modelowanie, przepięcia piorunowe, symulacje, EMTP/ATP

Introduction

Continuous efforts to increase the reliability of the electrical energy supply necessitate working out power systems which should to be so designed, run and maintained as to minimize the probability of the system failures. One of the fundamental requirements for a highly reliable electrical energy supply is assuring the continuity of work of transmission systems, mainly composed of overhead high voltage lines. A reliable operation of the transmission and distribution systems can be ensured by components with an insulation system designed for electrical strength, suitable for the expected stresses. On the other hand, there is a tendency to decrease insulation levels, mainly for the economic reasons. These contradictory suggestions necessitate the optimization of a technical solution of insulation systems. This requires a detailed analysis of stresses to which these systems are exposed. The main part of the transmission lines stresses, defining requirements for the power system insulation and crucial for its reliable operation are overvoltages. It is particularly overvoltages generated during lightning discharges, whose maximal values may be many times higher than the network voltage, which are responsible for the basic hazard of the insulation breakdown [1 - 7].

Overvoltages generated by lightning discharges to shielding wires or phase conductors of transmission lines are a result of complex, nonlinear and surge phenomena occurring in the structure of lines and electrical substation when the lightning current is flowing through them. Power systems are too complex for analytical solutions, therefore not even one simple problem can be usually sorted out. For this reason, such analyses are frequently based on computer simulations of overvoltage phenomena. In the simulation programs suitable models of electrical equipment and transient phenomena of the electric power systems should be implemented.

Selected models electrical power devices and physical phenomena during lightning discharges were presented in the paper [8-13]. Simulation results of lightning overvoltages performed with the Electromagnetic Transients Program/ Alternative Transients Program (EMTP/ATP) were done. This program is very often used for the simulations of transient phenomena in operating conditions in high voltage electrical networks, also lightning overvoltages. Especially the influence of the lightning current mathematical model used for simulating lightning overvoltages generated in high voltage electrical power systems with overhead transmission lines was analyzed.

The analyses provided practical insights about the consequences of selection of a specific kind of lightning current model on the overvoltage protection as well as on theoretical and practical aspects of the insulation coordination in high voltage power systems.

Models of lightning current

The time course of lightning currents have been analyzed in many publications [4,10,14-18]. Two models of lightning current very often used in technical practice, i.e. model proposed by the CIGRE and Heidler's model will be used in the following analysis. These models are implemented in EMTP/ATP.

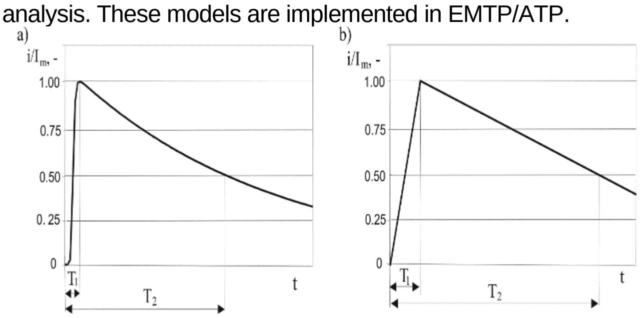

Fig. 1. Models of lightning stroke current: a - Heidler's model, b - model proposed by CIGRE [4,10,18,19]

Heidler's model of lightning current (Fig. 1a) [10,18] is expressed in the following form:

(1) $$i_p(t) = \frac{I_m}{k}\frac{(\frac{t}{T})^{10}}{1+(\frac{t}{T})^{10}}e^{-\frac{t}{\tau}}$$

where: I_m - peak current, kA,
$k = 0.986$, T=19 μs, τ = 485 μs - for first positive discharges, if I_m = 200 -1 50 kA (T_1/T_2 =10/350 μs),
k = 0.93, T=19 μs, τ = 483 μs - for first positive discharges, if I_m ≤100 kA (T_1/T_2 =10/350 μs),
k = 0.986, T = 1.82 μs, τ = 285 μs - for the first negative discharges, if I_m ≤100 kA (T_1/T_2 =1/200 μs),
k = 0.993, T = 0.454 μs, τ = 143 μs - for the subsequent negative discharges, if I_m ≤50 kA (T_1/T_2 =0,25/100 μs) [18].

According to CIGRE the lightning current time course has a triangle form (Fig. 1b) [4,10,19]. Time T_1 is calculated with the use of the following formula:

$$T_1 = \frac{I_m}{S_m} \tag{2}$$

where: I_m - peak current, kA, S_m - maximal steepness of lightning current (S_m = 24.3 kA μs^{-1} - for the first stroke, S_m = 39.9 kA μs^{-1} - for the subsequent strokes), T_2 - wave tail time to half value, μs (the median value of T_2 is 77.5 μs and the average or mean of T_2 is 91.5 μs).

Modelling of electrical power systems for the simulation of lightning overvoltages

A detailed model of the part of the electrical power system with overhead transmission lines was prepared for modelling lightning overvoltages. Among the modeled parts were overhead lines, grounging systems, towers, insulators, back flashover phenomena in the insulators and surge arresters.

The simulations of transient voltage and currents in power systems overhead transmission lines was represented by multi-phase models considering the distribution nature of the line parameters due to the range of frequency involved. The JMarti's and Semlyen's models of overhead lines, implemented in the EMTP/ATP took into account the frequency dependences of phase and shielding conductors parameters [10].

Towers for high voltage overhead transmission lines, modelled as short lines, were modelled taking into account their surge impedance and length [20 - 22].

The impulse resistance of an earthing systems of towers was approximated with the use of the formula [26]:

$$R_u(i) = \frac{R_{st}}{\sqrt{1+\frac{i}{I_g}}} \tag{3}$$

where: $I_g = \rho_e \frac{E_g}{2\pi R^2_{st}}$ R_{st} - static resistance of grounding system, Ω, E_g - soil ionization electric field strength, V m^{-1} (E_g = 300 - 400 kV m^{-1}), ρ_e - resistivity of soil, Ω m (ρ_e = 100 - 300 Ω m).

The insulators were represented by capacitors connected between the phase conductors and the tower: 80 pF/unit for suspension insulators and 100 pF/unit for the pin insulators [23].

The back flashover or flashover mechanism of the insulators were represented by the leader development method. The method was partly based on experimental results which in turn led to some analytical formulations. A set of differential equations leader development was solved, and then volt-time breakdown characteristic was obtained in a numerical process which could be related to physical phenomena. In the numerical algorithm, the first leader velocity was empirically formulated as a function of applied voltage, leader length, gap length, gap geometry and electric field intensity with two contributing factors, i.e. leader core and corona cloud. The time to the breakdown t_c can be expressed as [4,24 - 26]:

$$t_c = t_i + t_s + t_l \tag{4}$$

where: t_i - corona inception time (assumed zero), s, t_s - streamer propagation time, s, t_l - leader propagation time, s.

For t_s it is possible to write the following formula:

$$\frac{1}{t_s}\int_0^{t_s} u(t)\,dt = a \tag{5}$$

where: a = 400 g + 50 - for positive polarity voltage, kV, a = 450 g +150 - for negative polarity voltage, kV, $u(t)$ - voltage on insulator, kV, g - gap length, m.

For t_l:

$$\frac{d\,l_i}{dt} = k\,u(t)\left[\frac{u(t)}{g-l_i} - E_o\right] \tag{6}$$

where: E_0 - minimum leader progression electric field strength, V m^{-1}, l_l - leader length, m, k - leader coefficient, m^2 kV^2 s^{-1}.

Table 1. Values of k and E_o for practical configuration [23]

configuration	polarity	k m^2 kV^2 s^{-1}	E_o kV m^{-1}
air gaps	positive	0.8	600
post insulators	negative	1.0	670
cap and pin	positive	1.2	520
insulators	negative	1.3	600

Using the differential equation (6) the leader length can be solved as a function of time. The breakdown occurs when the leader length l_l is equal to the gap length g. This method can yield the breakdown volt-time characteristic of a long gap with any impulse wave in extremely short time (e.g. less than 1 μs impulse rise time).

Surge arresters were represented by high frequency model of IEEE Working Group 3.4.11 [27].

Characteristic of part of 220 kV electrical power system with overhead transmission lines

Overvoltages generated during lightning strokes to overhead transmission lines in part of 220 kV electric power system were simulated with the EMTP-ATP [10] (Fig. 2). Two different models of lightning current (Fig. 1) were used in simulations.

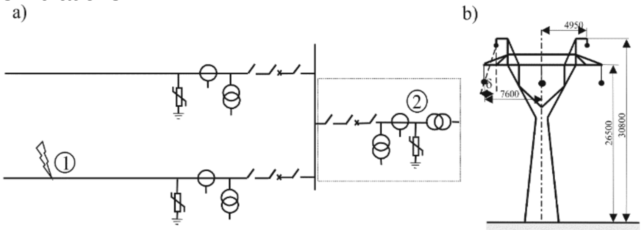

Fig. 2. a - single line diagram of the part of the electrical power system of 220 kV: 1 - point of lightning discharge and simulation of overvoltages at the tower, 1,2 - the points for simulations of overvoltages, b - basic dimensions of tower of 220 kV [28]

The overhead transmission lines of 220 kV supplied the power substation with an autotransformer 160 MVA, 220/110 kV (Fig. 2a). The cross section of phase conductors was 525 mm^2 that of shielding wires 70 mm^2. The line insulators were 1270 mm long [28]. The protection angle δ of the tower equaled to 22 grades (Fig. 2b). Despite the protection of the line with shielding wires to external phase conductors, lightning currents can strike. The maximum peak values I_{max} of lightning current which can strike to the phase conductor of the line was calculated with the formula [29-31]:

$$I_{pmax} = \left[\frac{\sqrt{d_{FO}^2 + (h_t - y)^2} + 2y}{1.34\,(h_t^{0.6} - y^{0.6}\,sin\,\delta)}\right]^{1.33} \tag{7}$$

where: h_t - shielding wire height, m, y - average phase conductor height, m, δ - the protection angle, deg, d_{FO} - horizontal displacement of phase conductor and shielding wire, m

Maximal value this current is equal to 14.08 kA.

For protection of the autotransformer metal oxide surge arresters of type PEXLIM P 192 were used [26,27,32].

Modelled part of electrical power system of 220 kV in EMTP-ATP

The complete model of selected part of the power system presented in Figure 2 prepared in EMTP/ATP is shown in Figure 3. The phase and shielding conductors of the overhead lines were represented by JMarti's model. Every span of the line was modelled as a selected part of the model. The model of a flashover on insulators took into account the leader development method and made use of formulas (5) and (6) in the environment MODELS of the EMTP/ATP [10]. The nonlinear voltage-current of earthing system of a tower was taken into account in the line model with formula (3). Line insulators were substituted by the condensators with capacitance of 100 pF. The autotransformer was modelled with the use of parallel connected transformer capacitance and winding surge impedance. The capacitance in the modelled autotransformer was 4.5 nF and surge impedance of high voltage windings 5000 Ω [33]. The current transformers of 220 kV were substituted by capacitors 420 pF. The capacitances of the potential was equal to 420 pF. Capacitance of measurment transformer was 810 pF. Circuit breakers were modelled by taking into account capacitances of insulators 50 pF and the capacitance of the insulator breaker 5 pF [33]. The inductance of connections between devices was taken into account too. Unit inductance of phase conductors equaled to 1.34 μH m^{-1} [33].

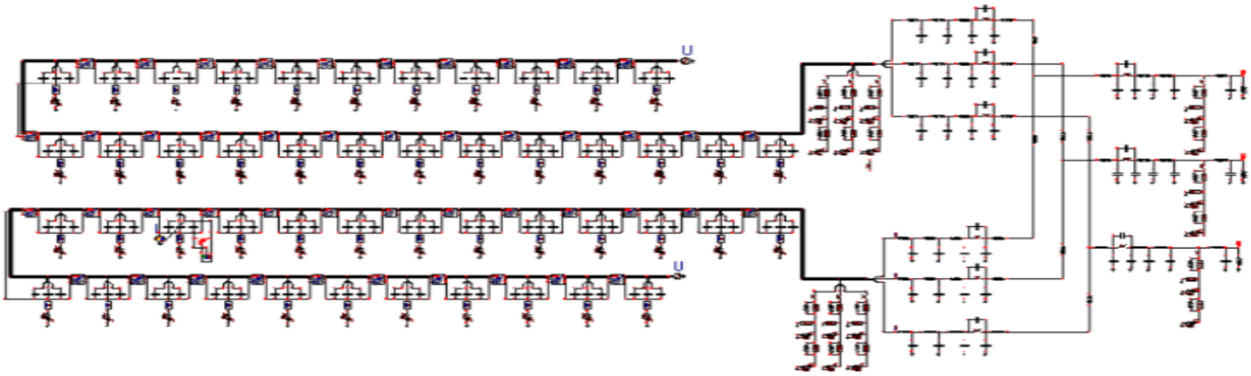

Fig. 3. Model of the part of electrical power system presented in Figure 2 used in simulations of lightning overvoltages prepared in *EMTP/ATP*

Results of simulations of overvoltages generated during lightning strokes to overhead transmission lines

Simulations were performed on the assumption that a lightning stroke occurred to the overhead line of 220 kV (point 1 - Fig. 2). The distance between the lightning stroke and the power station was 900 m. The lightning overvoltages were calculated for lightning stroke to shielding wires and to the phase conductor. Simulations were done for the lightning strokes with maximum value of 33.3 kA to the shielding wire (the median maximum value of lightning strokes) [4,6,19] and for the lightning stroke with maximum value of 14.08 kA to the phase conductor (equation (7)) [34].

Simulations were carried out for lightning discharges with extremely different courses, namely the first positive and successive negative discharges. Simulation results have a form of time courses of overvoltages on the tower of the overhead line of 220 kV (point 1 - Fig. 2a) and on the terminals of the transformer (point 2 - Fig. 2a) (Fig. 4,5). The maximal values of overvoltages are shown in Table 2.

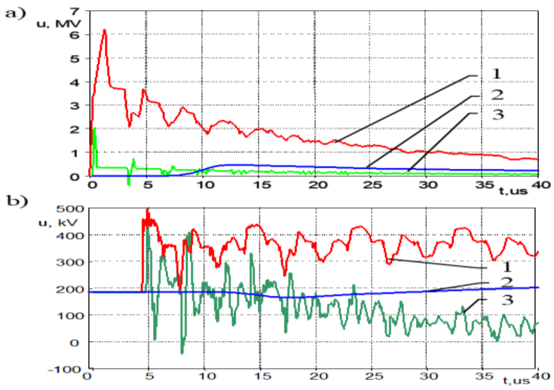

Fig. 4. Overvoltages at the part of the electrical power system of 220 kV (Fig. 2) simulated during lightning stroke to the shielding conductor (33.3 kA) in the point 1 of line: a - overvoltages at the tower (point 1), b - overvoltages between phase conductor and earth (point 2): 1 - *CIGRE* model for the first positive discharge, 2,3 - Heidler's model (2 - first positive stroke, 3 - subsequent negative discharge)

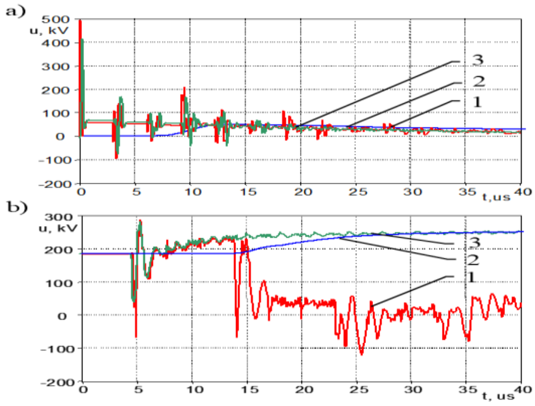

Fig. 5. Overvoltages at the part of the electrical power system of 220 kV (Fig. 2) simulated during lightning stroke to the phase conductor (14.08 kA) in the point 1 of the line: a - overvoltages at the tower (point 1), b - overvoltages between phase conductor and earth (point 2): 1 - CIGRE model for the first positive discharge, 2,3 - Heidler's model (2 - first positive stroke, 3 - subsequent negative discharge)

Table 2. Maximal values of overvoltages generated in selected points in the part of the electrical power system with overhead transmission lines 220 kV (Fig. 2) determined on the basis of the results of simulations (Fig. 4, 5)

the point of electrical power system (Fig. 2)	model of CIGRE lightning discharges	Heidler's model (first positive discharges)	Heidler's model (subsequent negative discharges)
	u		
	kV		
	33.3 kA (lightning stroke to the shielding wire)		
point 1	6000	500	2000
point 2	440	200	280
	14.08 kA (lightning stroke to the phase wire)		
point 1	420	90	280
point 2	240	240	240

The results of the simulations presented in Figures 4,5 and in the Table 2 shown that overvoltages generated in electrical overhead transmission systems during lightning discharges can have maximal values reaching megavolts and make much influence to high voltage insulation systems. Simulations reveal also that the selected lightning current model implemented in the EMTP/ATP and used in simulations has a great influence on the time courses and maximal values of calculated lightning overvoltages. The simulation results have a form of overvoltages with the highest maximal values when lightning current was modelled with the CIGRE model.

Summary

Method for simulating lightning overvoltages in high-voltage overhead transmission systems is presented in the paper. Models of power devices and physical transient phenomena occurring during lightning discharges in overhead transmission systems were characterized. The implementation of models for the simulation of lightning overvoltages in the EMTP/ATP was described in detail and calculations of such overvoltages were made in a part of the transmission system with 220 kV overhead lines. The results of overvoltage simulations, done for two lightning current models, are presented.

***Author**: prof. dr hab. inż. Jakub Furgał, AGH University of Science and Technology, Department of Electrical and Power Engineering, al. Mickiewicza 30, 30-059 Kraków, e-mail: furgal@agh.edu.pl.*

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