

Comparative analysis of lightning overvoltages in distribution lines on the ground of laboratory tests and measurements

W. SKOMUDEK*

EnergiaPro Energetic Concern Co., Department of Opole,
Technical University of Opole, Department of Electrical Engineering, Poland

Determination of extreme voltages induced on overhead and cable power lines by nearby lightning strokes is a complex problem. Results of computer simulation (laboratory tests) and measurements of such overvoltage processes due to lightning discharges occurring in overhead and cable lines, as elements of a distribution network, are presented. A principal, simulation tool was the PSpice program.

Key words: induced overvoltage; computer simulation; power line; lightning strokes

1. Introduction

Rapid development of industrial processes controlled by devices in which digital-circuit engineering is used obliges distribution companies to apply up-to-date techniques and technologies. It tends towards achieving of high quality and reliability of power networks. Beyond a doubt, one of serious causes of damages of network elements are direct and indirect lightning overvoltages [7–9, 21]. Such a threat concerns electrical equipment and particularly overhead and cable power lines. Distribution networks of middle voltage (MV) include traditional overhead power lines with bare conductors or more and more frequently with covered conductors and, furthermore, power cable lines composed of three single bundle assembled cables, placed in the ground or in the air (under slung on supports).

Influences of lightning surges on power lines according to produced harmful effects can be divided into influences being operational hazard caused by excessive electrical strength within line insulation systems leading to their degradation and influences posed a threat to the environment (electric shock hazard). In the former case

*Corresponding author, e-mail: waldemar.skomudek@pse-operator.pl

a measure of influences are induced overvoltages of high amplitude and frequency during a transient state in the circuit composed of a conductor and a thunderstorm cloud caused by electromagnetic field (generated by a lightning current). The other case is related first of all to electromagnetic field as a consequence of passage of lightning current by metallic coating of cables; a measure of dangerous influences in this instance is the voltage between the metallic coating and the ground.

Theoretical considerations dealing with overvoltages induced on power networks can be based on mathematical models worked out by Rusck, Agraval or Taylor [1, 3, 4, 6, 13, 20]. The principle for description of line elements pertinent to conditions of induced overvoltages is a general Maxwell equation in vectorial form:

$$\nabla^2 \mathbf{E} = \mu\epsilon \frac{\partial^2 \mathbf{E}}{\partial t^2} \quad (1)$$

equivalent to three scalar equations in the Cartesian coordinate system:

$$\begin{aligned} \frac{\partial^2 E_x}{\partial x^2} + \frac{\partial^2 E_x}{\partial y^2} + \frac{\partial^2 E_x}{\partial z^2} &= \mu\epsilon \frac{\partial^2 E_x}{\partial t^2} \\ \frac{\partial^2 E_y}{\partial x^2} + \frac{\partial^2 E_y}{\partial y^2} + \frac{\partial^2 E_y}{\partial z^2} &= \mu\epsilon \frac{\partial^2 E_y}{\partial t^2} \\ \frac{\partial^2 E_z}{\partial x^2} + \frac{\partial^2 E_z}{\partial y^2} + \frac{\partial^2 E_z}{\partial z^2} &= \mu\epsilon \frac{\partial^2 E_z}{\partial t^2} \end{aligned} \quad (2)$$

where each component of the electric field intensity vector $\mathbf{E}$ satisfies the wave equation.

In real power networks, due to dissipation of high-variable electromagnetic field, the following tendencies are observed: decrease of peak voltages and change of wave-forms during a nonstationary state. Suppression and deformation of waves (caused by influence of a series resistance of conductors, change of soil resistivity of soil, and occurrence of dynamic corona) can be modelled on the ground of processing programs.

However, owing to computer techniques:

- analyzes of induced lightning overvoltages are facilitated,
- mathematical model of lightning discharge canal has been perfected,
- solution of complex equations describing electromagnetic field has been simplified,
- a model of power system elements has been more detailed,
- computer simulations enable us to record variation of overvoltages at various points of an analyzed network area.

Evaluation of overvoltage hazard dealing with power line and cable insulating systems in various networks has been presented in numerous papers [2, 10, 11, 12, 16]. It has been pointed that application of PSpice program (Design Center Eval packet) to simulate transient states caused by lightning overvoltages is possible [14, 15]. Such

a statement is significant because PSpice program was intended in principle for electronic circuits.

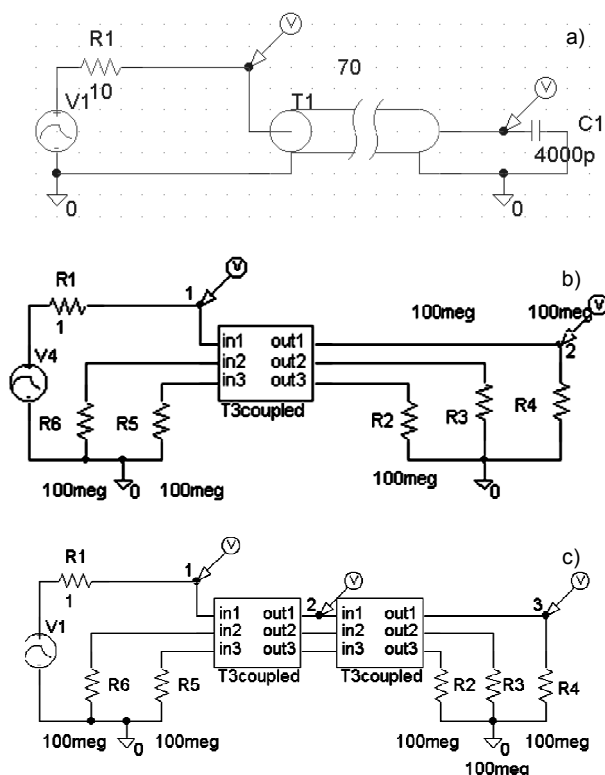


Fig.1. Schematic diagrams of the sections of simulated systems composed of:

a) overhead line segment, b) cable line segment, c) mixed system segment.

V1, V4 – input pulse sources, R1 – internal resistance of a source, C1 – capacitance, T1, T3 – models of power overhead line and cable line, R2–R6 – loading resistances

In the paper, the results of computer simulation of transient states due to direct and induced lightning overvoltages have been compared with the results of laboratory tests of models and those of measurements of overvoltages in real conditions. The latter case concerns power MV lines operated in a mixed system, i.e. overhead line connected with a cable line of different lengths. Final conclusions are formulated based on results of computer simulation.

2. Computer simulations

Computer simulation of transient states resulting from atmospheric discharges realized by means of processing programs, enables one to analyze transient states occurring within electric (electronic) systems in real time. Such programs, also employed to

design overvoltage protective systems, can be of various types depending on their function. The most known are Electro-Magnetic Transients Program program (EMTP) and Simulation Program with Integrated Circuits Emphasis (PSpice program) but others programs are also used to analyze of selected electrical processes. It is important that results of simulation should be verified (in respect of their quantity and quality) by comparing them with results of measurements related to physical models or – better – to real technical objects.

During numerous measurements and simulations a certain regularity has been noticed: wave front time of excitation impulse affects visibly overvoltages in particular elements of a power system. In order to confirm a level of overvoltage hazard and to determine the influence of wave-front time duration on rate-of-rise of the voltage stressing insulation, a computer simulation (using PSpice program) has been carried out [5].

Quick-variable passages of electromagnetic energy cause overvoltages of very high frequencies so each power overhead line and cable line during simulation should be treated as an element with distributed parameters. The following parameter values have been admitted:

- cable line ($C_0 = 0.1 \mu\text{F/km}$; $L_0 = 0.49 \text{ mH/km}$; $R_0 = 0.0289 \Omega/\text{km}$; $Z_0 = 70 \Omega$; $v = 142.86 \text{ m}/\mu\text{s}$)
- overhead line ($C_0 = 7,37 \mu\text{F/km}$; $L_0 = 1.71 \text{ mH/km}$; $R_0 = 0.35 \Omega/\text{km}$; $Z_0 = 482 \Omega$; $v = 281.69 \text{ m}/\mu\text{s}$).

Stimulation of design systems is an impulse (pulse) with exponential edges and variable values of parameters (Fig. 2). Simulations have been carried out for three systems presented in Fig. 1.

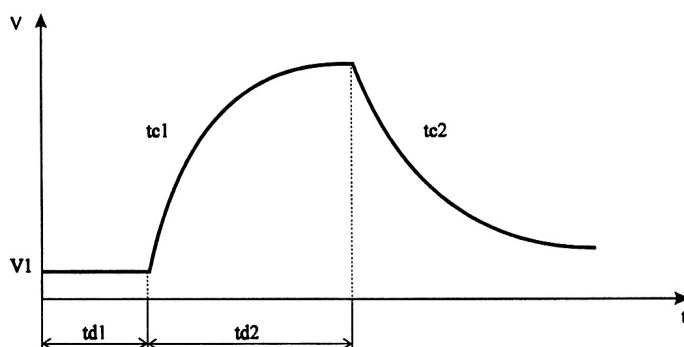


Fig. 2. Stimulation of a design system with exponential characteristic, accessible in PSpice program: t_{d1} – rise delay, t_{d2} – fall delay, t_{c1} – rise time, t_{c2} – fall time

Equivalent active parameters of power line conductors during overvoltages increase their values due to a skin effect. Such a phenomenon occurs also in a layer of

the soil and affects inductance of lines. In turn, dynamic coronas change capacities of lines. Each of these phenomena influences: wave impedance, velocity of wave propagation along conductors and deformation of impulse waves (Fig. 3c).

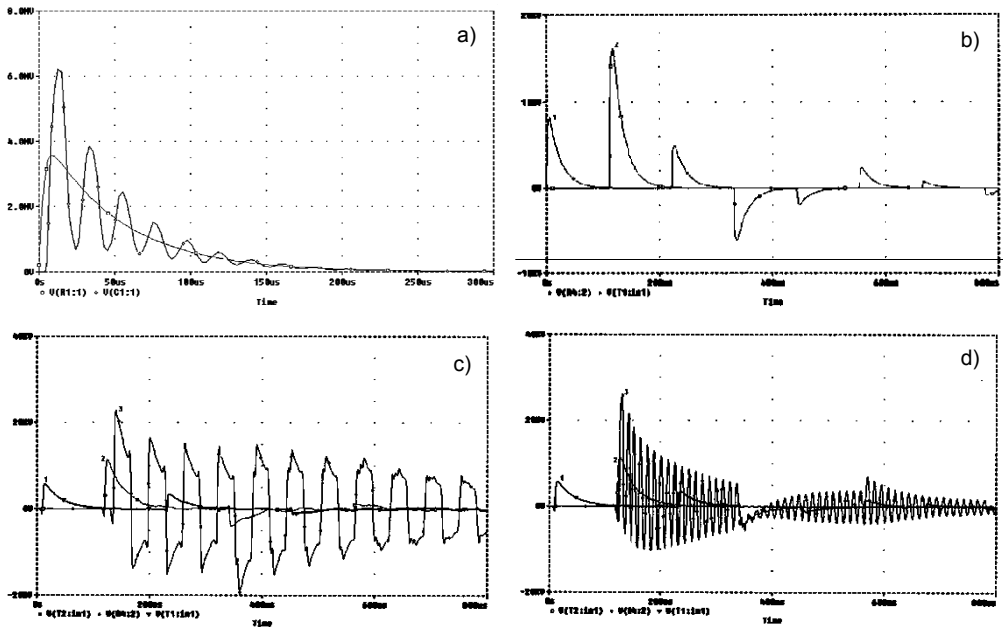


Fig. 3. Chosen time-dependent overvoltages occurring at points fixed in Fig. 1 for:
a) one-phase overhead line, b) three-phase cable line, c) three-phase mixed system of overhead
 $l = 5000$ m and cable line $l = 500$ m and d) three-phase mixed system of overhead
 $l = 1000$ m and cable line $l = 500$ m

Prospective failure frequency of MV power network elements due to lightning strokes is considerable. In some cases, that may lead to multiple damages of insulating systems. It has been proved by mathematical analyses and computer simulations (Fig. 3d). On the other hand, internal overvoltages generated during transient states are not a significant threat because impulse strength of insulating systems is much higher than prospective peak values of internal overvoltages.

Results of simulation prove that each direct lightning stroke in electric power elements and almost each nearby lightning stroke causes multiple reflections of waves leading to flashover or breakdown of insulating systems (Fig. 3). Occurrence of such breakdowns at many places of power cable lines is a very probable event.

The highest value of the voltage stressing insulating systems during lightning overvoltages depends positively on time parameters describing an overvoltage, i.e. time-constants t_{c1} and t_{c2} (relating to an aperiodic component of rise/fall delay of the wave). Time-dependent overvoltages in Fig. 3 are damped; they pose a threat to insulating systems as amplitude of stimulating signal increases or shape factor value the signal decreases (Fig. 4).

Computer simulation enables us to obtain numerous time-dependent overvoltages which prove that wave-front time of these overvoltages does not affect rate-of-rise of the voltage stressing insulating systems within individually screened cables. However, such a regularity is not confirmed towards belted cable.

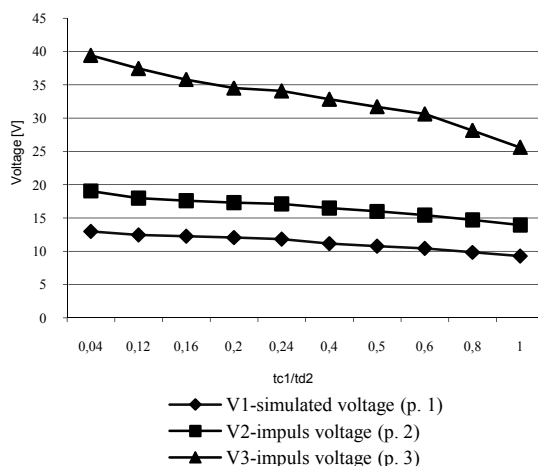


Fig. 4. Levels of voltage induced at measuring points 1, 2, and 3 from Fig. 1c depending on shape factor of stimulation pulse value – t_{c1}/t_{c2} (Fig. 2)

In the case of belted cables (network elements of frequent occurrence) decreasing of slope of the wave-front (input pulse) causes additional displacement of response amplitude towards longer lines; such a regularity has been proved during laboratory tests and investigations of real systems (Figs. 6a and 8). A displacement of response amplitudes during lightning overvoltages is caused by heterogeneity of metallic coating which affect increase of electromagnetic field dissipation and wave impedance of cables with not screened conductors in respect of cables with concentric conductors.

3. Laboratory tests and investigations in selected real lines

Results obtained from the simulation process have been verified based on the measuring system made both for single-core screened and three-core belted cables (Fig. 5). The system was equipped with a special pulse generator which allows us to regulate the slope and wave front duration. In the case of three-core line only the generator of rectangular pulses energized one from all the conductors.

Transient time-dependent voltages caused by the pulse in the energized conductor (in the three-core line and in non-energized neighbouring conductors) have been recorded by means of a multi-channel digital oscilloscope. The obtained transients reveal that pulse time parameters at the input of the examined system have great impact on the shape of reflected and induced waves in neighbouring cable wires. However, in

the case of unscreened cables, lowering of the input pulse inclination causes additional shifting of reflection amplitude to longer timing.

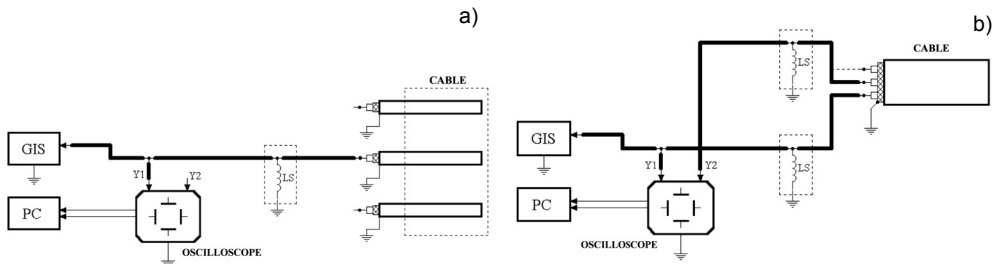


Fig. 5. Scheme of the measuring system [14] for: a) single-core concentric line, b) three-core belted cable; LS – system protection, Y1, Y2 – oscilloscope canals, GIS – pulse generator

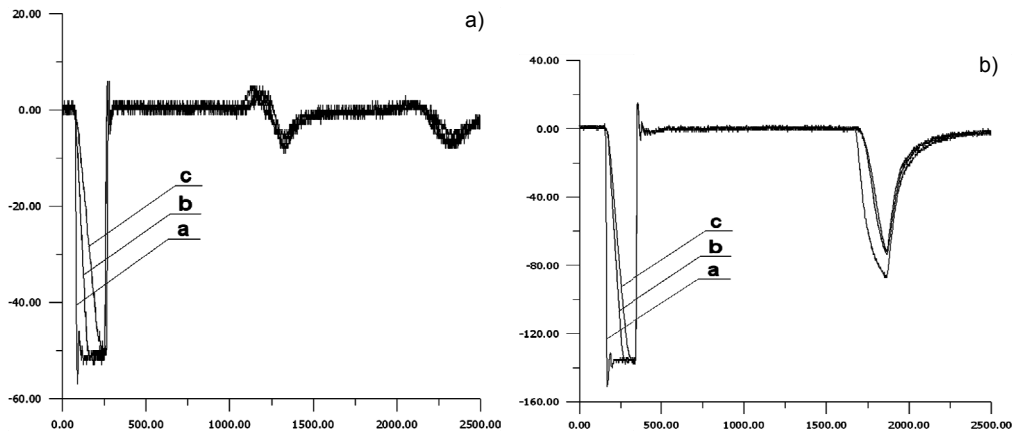


Fig. 6. Time-dependent overvoltages occurring in line models [13]:
a) traditional three-core, b) single-core; input signal: amplitude 4.1 V, breadth $\Delta t = 250$ ns;
a, b, c – input impulses V_a , V_b , V_c for various pulse rise times

Results of laboratory tests, carried out for two chosen type of lines, are presented in Fig. 6. Recording of time-dependent overvoltages in real overhead/cable lines between high voltage station Prudnik and medium voltage-to-low voltage station Oczyszczalnia has been made similarly [17, 18]. As a source of stimulation, a 12 kV test transformer was used. Chosen test results for various pulse rise times of wave front overvoltage are presented in Fig. 7.

Initiation of travelling waves in power network leads to occurring of periodical variable voltages (overvoltages) at the ends of power lines as an effect of multiple wave reflections. Such overvoltages, after several periods, cause considerable deformation of waves in comparison with a stimulation pulse.

Shapes, amplitudes and reciprocal displacements of overvoltages recorded during tests (Figs. 7, 8) are compatible with theoretical wave phenomena. Investigations carried out in network elements [19] and in laboratory models confirm results

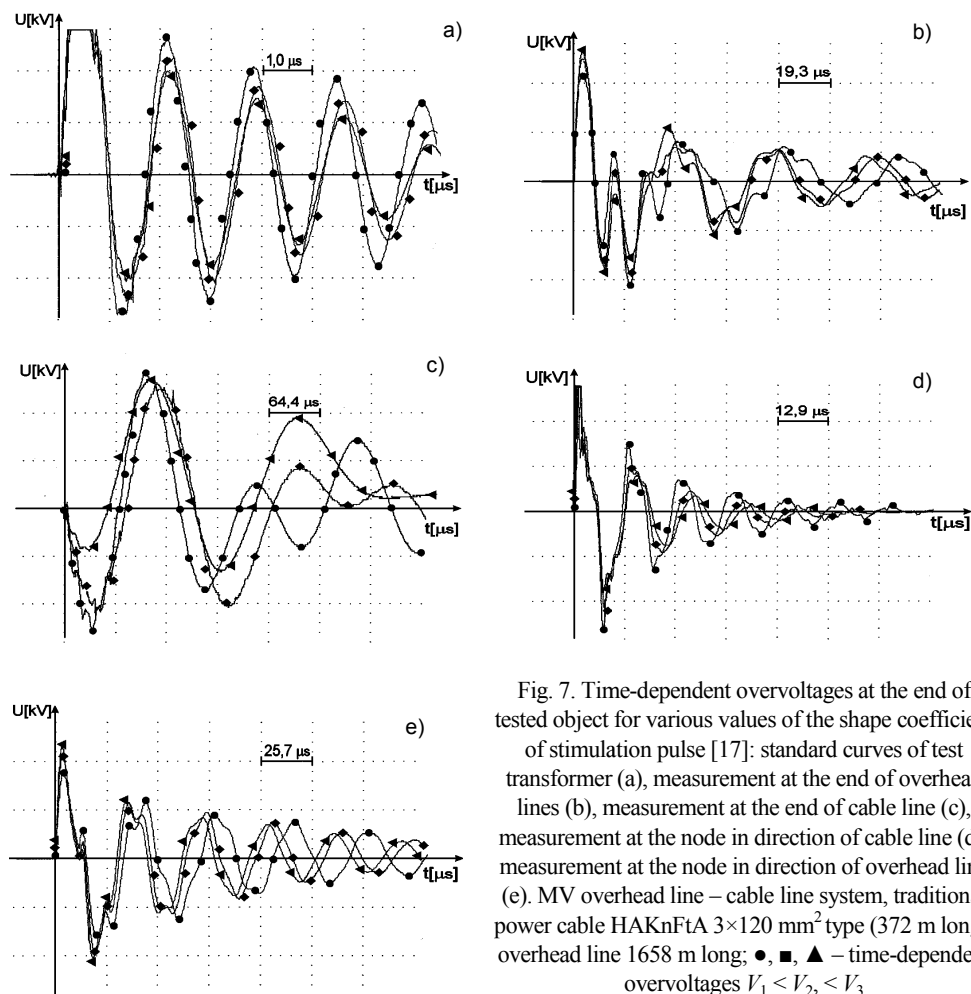


Fig. 7. Time-dependent overvoltages at the end of tested object for various values of the shape coefficient of stimulation pulse [17]: standard curves of test transformer (a), measurement at the end of overhead lines (b), measurement at the end of cable line (c), measurement at the node in direction of cable line (d), measurement at the node in direction of overhead line (e). MV overhead line – cable line system, traditional power cable HAKnFtA $3 \times 120 \text{ mm}^2$ type (372 m long), overhead line 1658 m long; $\bullet$, $\blacksquare$, $\blacktriangle$ – time-dependent overvoltages $V_1 < V_2 < V_3$

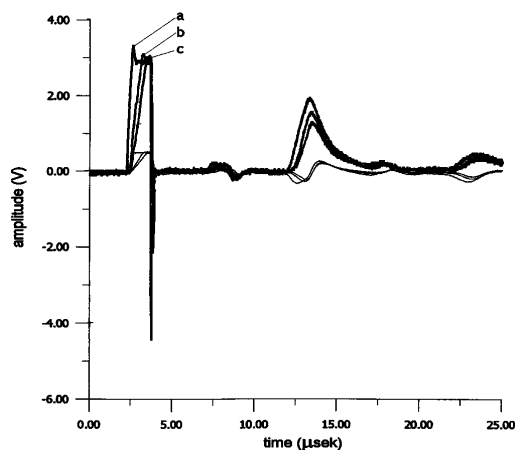


Fig. 8. Time-dependent overvoltages in the traditional three-core cable line for various pulse rise times [17]; underground cable AKFtA $3 \times 120 \text{ mm}^2$ type; a, b, c – input impulses V_a , V_b , V_c for various pulse rise times

of computer simulations concerning the nodes and points of discontinuity where wave impedance undergoes changes. However, it is advisable to verify additionally the obtained results by means of other processing programs (e.g., EMTP). It aims also at selection of the most suitable informatics tool to analyze transient states in power networks.

4. Conclusions

- Tests and many years of observations of atmospheric discharges show that peak value and steepness of wave front are random values of negligible correlation. This means that these parameters can be analyzed independently.

- Analysis results of computer simulations, laboratory tests, and measurements in real power networks prove that time duration of an overvoltage does not affect the rate of rise of the voltage stressing insulating systems in overhead lines. Such a conclusion is true for individually screened cables. Dominant influence of the voltages stressing insulating systems in line elements, due to overvoltage processes, are their parameters: the rate of rise and time duration of a wave.

- PSpice program applied to analyze overvoltage processes in power systems enables one to reproduce easily a stimulation pulse, to observe propagation of voltage waves in the first phase of a transient state and afterwards – when a wave reaches a node point. An analysis of the influence of wave processes in multiple conductor lines on the overvoltages in particular conductors is possible too.

- An analysis of time dependent voltages as a result of simulation processes with models accessible in the program shows that PSpice program is a convenient simulation tool, although obtained models do not take into account two essential phenomena: skin and corona effects during transient states. Such imperfections overstate amplitudes of signals returned from the lines.

- Due to dynamic corona effect, the velocity of wave propagation decreases nonlinearly when actual values of impulse voltage increase. This causes a favourable effect consisting in deformation of impulse waves and in decrease of their slopes.

References

- [1] AGRAWAL A.K., PRICE H.J., GURBAXANI S.H., IEEE Trans. Electromagn. Compat., EMC-22 (1980), 119.
- [2] ANDREOTTI A., DE MARTINIS U., VEROLINO L., Adv. Eng. Software 31 (2000), 757.
- [3] BAJOREK J., GAMRACKI M., *Effectiveness of mathematical modelling of lightning coupling to overhead conductors*, Proc. 26th Int. Conf. Lightning Protection, Cracow, 2002, 208–213.
- [4] BAJOREK J., MASLOWSKI G., *Mathematical models of electromagnetic field of lightning*, Proc. 22nd Int. Conf. SPETO, Gliwice–Ustroń 1999, 97–100.
- [5] BARANOWSKI K., WELO A., *Simulation electronics chosen. MIKOM*, Warsaw, 1996 (in Polish).
- [6] COULSON C.A., JEFFREY A., *Waves, mathematics models*. WNT, Warsaw, 1982.
- [7] FLISOWSKI Z., KOSZTALUK R., Przegl. Elektrotechn., No. 2, 1997 (in Polish).

- [8] GACEK Z., SKOMUDEK W., *An analysis of overvoltage hazard due to lightning discharges in medium voltage overhead lines with covered conductors*. Proc. of the 12th Int. Symp. High Voltage Engineering – ISH, Delft, 2003, 77.
- [9] GACEK Z., SKOMUDEK W., *Energetyka*, No. 1, 2003 (in Polish).
- [10] KRAFT L.A., *IEEE Trans. Power Syst.*, 6 (1991).
- [11] MCDERMOTT T.E., SHOT T.A., ANDERSON J.G., *IEEE Trans. Power Delivery*, 9 (1994).
- [12] NUCCI C.A., RACHIDI F., IANOZ M., MAZZETTI C., *IEEE Trans. EMC*, 35 (1993), 75.
- [13] RUSCK S., *Induced lightning overvoltages on power transmission lines with special reference to the overvoltage protection of low voltage networks*. Ph.D. Thesis, the Kungi, Tekniska Hogskolan, Stockholm, Sweden, 1957.
- [14] SKOMUDEK W., *J. Electr. Eng.*, No. 5–6, Slovakia, 2004.
- [15] SKOMUDEK W., *Evaluation to make use of PSpice program to modelling lightning inducted voltages of power systems*. Computer Application in Electrical Engineering, Zakopane, 2005.
- [16] SKOMUDEK W., GACEK Z., *Influence of selected parameters of overvoltages on hazard of insulating systems in MV power lines*. Electronic and Electrical Engineering, No. 2, Lithuania, 2006.
- [17] SKOMUDEK W., *Registration of time dependent overvoltages in authentic overhead/cable lines between 15/0.4 kV switching stations: Prudnik and Oczyszczalnia Prudnik*. 7, 2004 (in Polish).
- [18] SKOMUDEK W., *Registration of time dependent overvoltages in authentic cable lines in GSZ Cementownia Góraždze*, Chorula, 11, 2004 (in Polish).
- [19] TARCZYŃSKI W., SKOMUDEK W., *Wave phenomena in MV cable lines*, Rep. from own tests, Opole 2004 (in Polish).
- [20] TAYLOR C.D., HARRISON C.W., SATTERWHITE R.S., *IEEE Trans. Antennas Propagat.*, AP-13, 1965.
- [21] YOKOYAMA S., *IEEE Tran. Power App. Syst.*, 103 (1984).

Received 20 April 2007

Revised 21 July 2007

Proszę podać nr strony w Ref. 10, 11, 20, 21