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COMMUNICATIONS

COMPUTER ANALYSIS OF OVERVOLTAGE HAZARD DUE TO LIGHTNING DISCHARGES IN MEDIUM VOLTAGE OVERHEAD LINES WITH COVERED CONDUCTORS

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Evaluation and computer simulation results regarding overvoltage hazard due to lightning discharges occurring within MV (20 kV) overhead power lines equipped with covered conductors are presented. Overvoltages due to direct and indirect lightning strokes are under consideration.

Keywords: over-voltage hazard, computer simulation, overhead and cable power lines of medium voltage

1 INTRODUCTION

Specific medium voltage (20 kV) overhead power lines with cover conductors (the so-called PAS system) are not equipped with bare conductors but covered ones, i.e. covered by a thin resin insulating layer. In effect of such a modification new functional features bring to light - in particular considerable less faults and disturbances than in the case of traditional lines [1, 6]. However, overvoltages can threaten these specific lines during thunderstorms and such hazard, caused by direct and nearby lightning strokes, is analysed in the paper.

2 HAZARD DUE TO LIGHTNING DISCHARGES

Lightning hazard is connected with the so-called thunderstorm activity in a given area, evaluated either by means of thunderstorm maps or distant-reading registrations of electromagnetic effects by means of a lightning location system (LLS). Thunderstorm maps contain closed lines that join points with the same average number of thunderstorm days/year (D). In Polish area the mean value of this number $D = 20$ day/year, so the average lightning strike density can be estimated on the level of $N_r = 1.9$ str/km^2/yr [4, 5]. For the purpose of this paper only the most frequent negative lightning strikes (20-30 kA) are considered. The lightning stroke number in one year (N_L), calculated for a line with length is l (in km) and the average height is h (in m) can be estimated basing for example on empirical relationship: $N_L = 0.027 N_r l h^{0.5}$ 5, [4]. For $h = 10$ m and a segment line of 1 km the average lightning stroke number is $N_{L1}1 = 0.162$ str./km yr. Taken into account that:

- typical expected lightning stroke currents comply with values in Table 1,
- wave impedance of the conductor is 482 W [8],
- surge resistance to earth of overhead line support is approximately 10 W,
- the BIL of insulating system composed of the insulator and insulating covering on the conductor is $125 + 90 = 215$ kV [8],

then each direct lightning stroke to line conductors and almost each stroke to line supports may cause either a flashover on insulators or a breakdown of insulating covering. Such events can take place simultaneously in several points of the power line.

Table 1. Cumulative distribution of lightning stroke current magnitude $P(i_s \geq i)$, [7]

Stroke current i (kA)	Probability $P(i_s \geq i)$
2	0.999
5	0.991
10	0.750
31	0.500
50	0.224
70	0.107
100	0.045
200	0.014

Considerable overvoltages are caused not only by direct but also by indirect lightning strokes to nearby ground [3, 8]. The last ones involve the so-called induced overvoltages in line conductor systems near the point of the lightning stroke. They can be dangerous to insulation

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systems of MV power lines though their level is rarely over 200 kV. The analysis of induced overvoltages due to lightning strokes is facilitated by contemporary computing technique. In order to simulate such a process, various models of power lines with covered conductors during overvoltages can be used - *eg* Rusck's, Taylor's or Agrawal's models [2, 9].

According to Agrawal's model, used to quite precise analyses, there are two components of electric field vector: vertical $E_h(x,h,t)$ directed across the conductor, and horizontal $E_x(x,h,t)$ directed along the conductor (where h is the height above the ground of the conductor, x is the coordinate along the conductor, and t is time). Interaction of these components gives the total voltage of the conductor $u(x,t) = u_i(x,t) + u_s(x,t)$ as the sum of two addends: $u_i(x,t)$ connected with $E_h(x,h,t)$, and $u_s(x,t)$ connected with $E_x(x,h,t)$. The value of the first addend results from the relationship:

$$u_i\left(x,t\right) = -\int\limits_0^h E_h\left(x,h,t\right) dz \approx -E_h\left(x,h,t\right) h, \qquad (1)$$

whereas in order to calculate $u_s(x,t)$ the following system of equations should be solved:

$$\frac{\partial u_s(x,t)}{\partial x} + L^{\cdot}\frac{\partial i(x,t)}{\partial t} = E_h(x,h,t), \qquad (2)$$

$$\frac{\partial i}{\partial x} + C^{\cdot}\frac{\partial u_s(x,t)}{\partial t} = 0, \qquad (3)$$

where $i(x,t)$ is the real current in a line, L' and C' are respectively elementary inductance and capacitance of the line.

There is also a simpler way for evaluation of induced overvoltages [4, 9]. The maximum value of total overvoltage (U_{max}) induced within covered conductors depends on several factors - above all on the distance between the lightning stroke channel and the line (d), the height above the ground of conductors (h), and the waveform of overvoltage. These factors can be accounted for by means of relevant coefficients (k) introduced to the following relationship:

$$U_{\max}(d) = k_u\, i_s\, \exp(k_0 + k_1 \ln d + k_5 \ln^5 d), \qquad (4)$$

where k_u depends on the height h and time-constants of lightning wave (*ie* time-constant relevant to the wave front and the crest of wave), whereas factors k_0, k_1 and k_5 depend on time duration of the wave front (t_w) and the time to half-value. Graphical illustration of the above relationship, for two time duration values of wave front, is presented in Fig. 1.

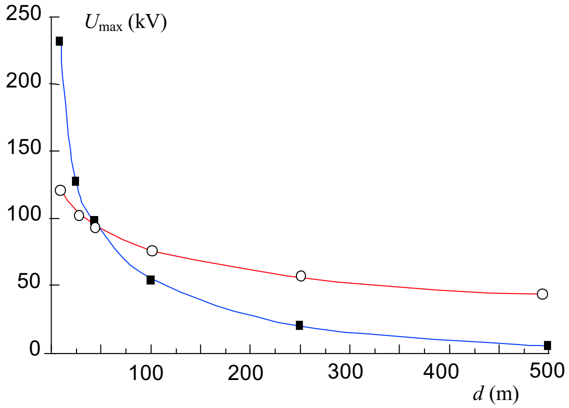

Fig. 1. An example of the relationship between the maximum value of total overvoltage induced in a 20 kV overhead line with covered conductors suspended 10 m above the ground for two values of wave front duration t_w [8]: ■ — $t_w = 0.5\,\mu$s, ○ — $t_w = 5\,\mu$s.

For average stroke values (correspond to $P = 0.5$) the first ($i_s = 30$ kA, $t_w = 5$s) and next ($i_s = 12$ kA, $t_w = 0.5\,\mu$s) induced overvoltages exceed the impulse strength of the conductor insulating layer (90 kV) when distance is $d \geq 58$ m. However, when $d \leq 20$ m, then the lightning stroke channel points directly toward the line conductors and neighbouring discharges do not occur. This means that lightning discharges can be dangerous for covered conductors of considered 20 kV power lines when the strokes are distant $d = 20$ to 58 m from them.

3 COMPUTER SIMULATION OF LIGHTNING OVERVOLTAGES

In order to analyse wave processes within power lines due to lightning discharges there are various computer techniques including software packages (*eg* EMTP - Electro-Magnetic Transients Program) or special processing programs. Computer analysis of overvoltages affected in MV power lines with covered conductors has been carried out using processing program PSPICE (Simulation Program with Integrated Circuits Emphasis) from the Design Center Eval Packet [7]. The schematic diagram of the equivalent model of the power line is presented in Fig. 2. Parameters calculated for 20 kV overhead power lines with covered and bare conductors are presented in Table 2. The input of the equivalent model has been stimulated by exponential impulses reproducing both overvoltages due to direct lightning strokes to a line support and induced overvoltages due to nearby ground. Real maximum values of these overvoltages taken for calculations are 4 MV and 0.25 MV, respectively. Computer calculations have been made for a line loaded by a small capacitance corresponding to a switching station.

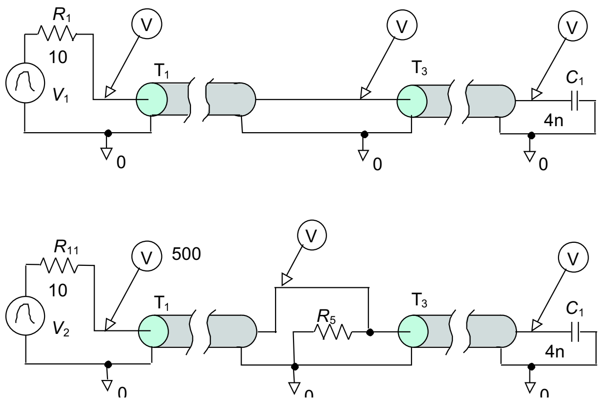

Fig. 2. Example of a schematic diagram of the equivalent model of MV power line with covered conductors connected in series with a segment of MV cable line: a) without surge protection, b) with a surge protective device. V1 - input impulse source; R1 - internal resistance of V1 source; R5 - protective resistor; T1, T3 - models of power overhead line and cable line (with loss of energy); C1 - capacitance.

Numerous transient time-dependent voltages have been obtained as computer simulation results. Examples of these relationships, relating to overvoltages due to direct lightning strokes to a line support, are presented in Figs. 3 and 4. Basing on such computer simulations the following opinions can be confirmed:

- lightning direct strokes to lines or even to their surroundings may cause multiple breakdowns of conductor insulating layers, particularly in lines without any surge protective devices, like surge arresters, arc gaps, arc protection device (APD) systems as well as at places where wave-impedance is considerable changing (*eg* cable heads);
- PSPICE program enables us to follow the voltage waves at a given nodal point both in the first phase of transient and after arrival of waves reflected from other nodal points.

Table 2. Choice parameters of 20 kV overhead power lines with covered and bare conductors [8]

Line	Parameter			
	C_0 pF/m	L_0 μ/m	Z_0 Ω	v m/μs
with bare conductors	6.62	1.68	503	299.85
with covered conductors	7.37	1.71	482	281.69
C_0, L_0, Z_0 are self-capacity, self-inductance and self-impedance of covered conductors.				

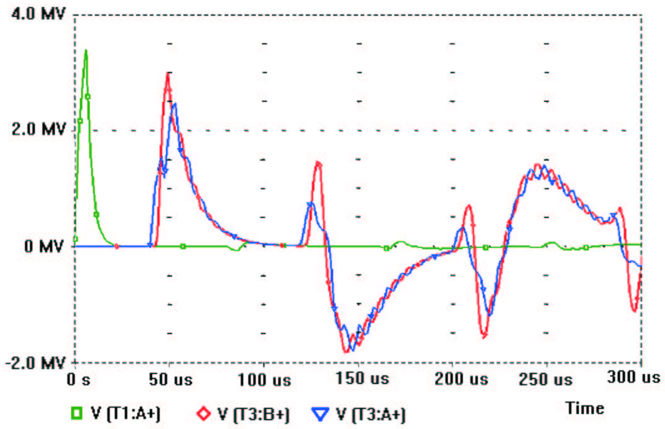

Fig. 3. Transient time-dependent voltages simulated for a system like in Fig. 2a. Overhead line T1: $Z_0 = 500\,\Omega$, $l = 12$ km; cable line T3: $Z_0 = 150\,\Omega$, $l = 450$ m; A, B - origin and end of a line.

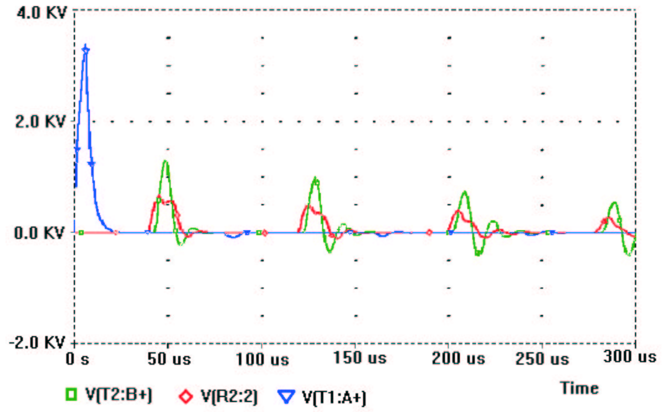

Fig. 4. Transient time-dependent voltages simulated for a system like in Fig. 2b. Overhead line T1: $Z_0 = 500\Omega$, $l = 12$ km; cable line T3: $Z_0 = 150\Omega$, $l = 450$ m; protective resistor $R_5 = 100\Omega$; A, B - origin and end of a line.

Surge arresters, arc gaps and APDs installed within lines increase the capital costs, therefore the choice of their rational concentration is an important practical task. In order to choose allowable maximum distances between such devices the maximum overvoltage values induced within 20 kV lines with covered conductors (due to nearby lightning strokes) has been calculated by means of C.A. Nucci's method (Table 3).

Calculations, based on formula (4), have been made for:

- different lightning stroke current values (is), both the first and next surges correspond to three probability levels,
- different distances between the lightning stroke channel and conductor of the line (d).

Calculation results allow searching for such points along the line where the impulse strength of insulation is equal to the induced overvoltage value. Detailed theoretical analysis and computer simulations prove that the allowable maximum distance between overvoltage protective devices should not be less than 124 m for the first lightning stroke or 104 m for the next ones [8]. Since the span length of 20 kV lines is within 90-150 m, then, in order to protect these lines against overvoltages, protective devices should be situated in each support. Such a suggestion is related only to lightning strokes with very small probability P=0.05, so practical principles regarding installation of protective devices seem to be more "tolerant" - *eg* at least in every third support of a line situated at flat area and without buildings, or at least in every fifth support of a line situated at forest area.

Table 3. Choice parameters of 20 kV overhead power lines with covered and bare conductors [8]

P	Parameters of **the first lightning stroke** *next lightning strokes*		Maximum induced overvolages U_{max} for different distances d			
	i_s	$(\frac{di}{dt})_m$	20 m	25 m	56 m	62 m
–	kA	kA/μs	kV			
0.95	**14**	**5.5**	**62**	**51**	**39**	**34**
	4.6	*12*	*89*	*70*	*32*	*29*
0.50	**30**	**12**	**121**	**110**	**92**	**74**
	12	*40*	*231*	*183*	*84*	*75*
0.05	**80**	**32**	**353**	**294**	**221**	**215**
	30	*120*	*578*	*458*	*215*	*189*

4 RECAPITULATION

MV power lines with covered conductors can be an attractive alternative to traditional overhead and cable lines. However, they must be effectively protected against lightning surges due to direct or neighbouring lightning strokes because solid resin covering on conductors is not a self-restoring insulation and expected hazard caused by lightning discharges can be considerable. Effective surge protection is possible by means of modern surge arresters as well as specific arc gaps and arc protection devices installed in several line supports.

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