ATP ANALYSIS OF TRANSMISSION LINES BEHAVIOUR ON DIRECT LIGHTNING STROKES

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REZUMAT. Lucrarea abordează comportarea liniilor aeriene de 400 kV la lovituri directe de trăsnet. Regimurile tranzitorii generate de lovituri directe de trăsnet în elementele liniilor sunt analizate cu ajutorul simulărilor în ATP-EMTP. Conturnarea izolatoarelor a fost simulată cu ajutorul caracteristicii tensiune-timp a acestora, precum şi prin folosirea unei abordări particulare a modelului liderului progresiv. S-a efectuat o analiză comparativă între rezultatele obţinute prin simulare şi cele obţinute prin modelele matematice clasice în ceea ce priveşte curenţii de protecţie şi numărul specific de deconectări.

Cuvinte cheie: trăsnet, conturnare, ATP, lider progresiv.

ABSTRACT. Several aspects concerning 400 kV overhead lines` behaviour on lightning direct strokes are presented. The transient regimes, generated by the lightning strokes in the active conductors, towers and sky wires are analyzed using ATP-EMTP simulations. The insulators` flashover is simulated considering their voltage-time characteristics and a specific approach of the leader progression model (LPM). Simulations' results and comparative analysis between these ones and those of the classical mathematical models, regarding protective currents and specific number of outages are presented.

Keywords: lightning, flashover, ATP, progressive leader.

1. INTRODUCTION

The overhead lines, due to their height, are the electric grids' elements the most exposed to the lightning strokes. Also, due to their length, quite big lightning's collection area results. Even if the insulation of the overhead lines is a self-healing one, the lightning strokes can initiate short circuits and lines' outages involving unfavourable effects over the power grids` operational reliability.

The issue of lines' behaviour at direct lightning strokes and at induced overvoltages, when lightning stroke in the proximity of the lines, is well presented in published books and papers. So, a sustained and well informed synthesis is presented in [1].

There are two approaches of overhead lines' behaviour at lightning strokes. Some analytical models determine the pulse voltages` time evolution, considering the repeated reflections, even at the towers' level [2,3]. The stress of the lines' insulators is analyzed on basis on parameters like: towers' surge impedance, pulse surge impedance of the grounding grid, the electrostatic and electromagnetic induced voltages, the modification of the coupling factors in presence of the corona discharge, the polarity of the pulse and line's span.

Others analytical models asses, only in a quantitative way, the lines` performance at lightning overvoltages on basis on specific number of outages indicator [4,5]. These often used models in estimation calculations operate with the voltages' and currents' peak values, having no interest for their time evolution.

If the first models' categories aim to determine the voltage-time evolution on line's insulation, the main stage of the second category is to determine the so-called protective currents.

Negative first strokes have traditionally been considered to produce the worst stress on transmission-lines' insulation. Subsequent negative strokes have significantly lower peak current but shorter wavefronts, so these ones may stress the insulation more than the first stroke, particularly for low footing resistances and tall structures.

Positive strokes have about the same median current value as the negative first strokes and longer fronts. However, the extreme current values of positive strokes tend to be higher than the negative strokes; hence both positive and negative strokes should be considered in the lightning simulations of overhead power lines [6]. In making simulations of lightning performance of overhead power lines, conservative values of stroke parameters are advised in presence of the many uncertainties. Until these uncertainties will be resolved, it is prudent to use those stroke values obtained by direct measurements and to recognize that approximations are inevitable. Until more data will be available it is recommended to use [6]: the CIGRE waveshape, whenever is possible; Heidler's formula for the negative first stroke and Anderson-Eriksson approximations for negative subsequent strokes and [6].

2. MODELS

2.1. MATHEMATICAL MODEL

The presented mathematical model refers to the estimation of the specific number of outages, in number of outages for 100 km line's length and along a year.

To calculate this indicator the local density of lightning strokes (D_l) must be known. This geographic parameter can be calculated as a function of local keraunicity (N_k):

$$D_l = 0{,}04 \cdot (N_k)^{1{,}25} \text{ or } D_l = \frac{1{,}1 \cdot N_k}{1 + 1{,}4 \cdot \sqrt{N_k}}. \quad (1)$$

Starting from a keraunicity of 35 ÷ 40 storm days/year these two formulas give similar results.

Number of lightning which stroke a 100 km line/year is

$$n_l = 0{,}6 \cdot h \cdot D_l, \quad (2)$$

where h is line's towers height and specific number of outages generated by direct lightning strokes results as:

$$n_{od} = n_l \cdot P_f \cdot P_a = 0{,}6 \cdot h \cdot D_l \cdot P_f \cdot P_a, \quad (3)$$

where P_f is the probability of flashover or back-flashover and P_a is the probability to transform pulse flashover into electrical arc maintained by the line's operational voltage (U_s). The pulse flashover probability can be calculated using the formulas of lightning current's intensity, P_f being the probability to have a pulse current higher then the protective current (I_p), this one being that current which determine on insulation a voltage equal with pulse flash-over voltage ($U_{50\%}$). Examples of such formulas are [1]

$$P_f = A \cdot e^{-I_p / B}, \quad (4)$$

where A and B depend on lightning's type, and [6]

$$P_f = \frac{1}{1 + \left(\frac{I_p}{31}\right)^{2{,}6}}. \quad (5)$$

For currents' intensities between 10 kA and 75 kA, the difference given by (4) and (5) formulas is less then 10 %.

P_a probability can be calculate with formula

$$P_a(\%) = 1{,}6 \cdot U_s / l_{ins} - 6, \quad (6)$$

l_{ins} being the axial length of line's insulators, multiplied with 2 when neutral grounding is Petersen coil type or insulated type.

A general formula as (3) must be making particular for overhead line's type. So, in the case of VHV lines, the specific number of outages generated by direct strokes is:

$$n_{od} = 0{,}6 D_l P_a \left\{P_\alpha h_c P_{fc} + (1 - P_\alpha) \cdot \left[\gamma h_t P_{ft} + (1 - \gamma) h_{gw} P_{fgw}\right]\right\}, \quad (7)$$

where P_α characterize the ground wires' fault shielding and γ gives the number of direct strokes on line's towers. Flashover probabilities must be calculated for each of line's constructive elements (active conductors – P_{fc}, towers – P_{ft} and ground wires – P_{fgw}), so the protective currents must be calculated for each of these elements.

The formulas to calculate protective currents can be very simple, as is that in the case of direct stroke in the medium voltage lines' towers

$$I_{ptMV} = \frac{U_{50\%}}{R_g}, \quad (8)$$

R_g representing the average value of the pulse resistance of the towers' ground electrode. On the other hand, in the case of power tgransmission lines the expressions of the protective current are more sophisticated:

$$I_{ptHV} = \frac{U_{50\%} - 0{,}5 \cdot U_s / \sqrt{3}}{(1 - k) \cdot \left(\kappa_1 \cdot R_g + \kappa_1^2 \cdot \frac{L_t}{t_f} + 0{,}5 \cdot \frac{h_{gw}}{t_f}\right) + \left(1 - k \frac{h_{gw}}{h_c}\right) \cdot \frac{h_c}{t_f}}$$

where

$$\kappa_1 = \frac{Z_k \cdot Z_{gw} / 2}{Z_k + Z_{gw} / 2} / \left(\frac{Z_k \cdot Z_{gw} / 2}{Z_k + Z_{gw} / 2} + R_g\right), \quad (9)$$

the other terms representing: towers' inductance (L_t), the wavefront time (t_f), the surge impedance of the ground wires (Z_{gw}), the surge impedance of the main lightning's discharge channel (Z_k), the minimum value of capacitive coupling factors between line's ground wires and phase conductors (k).

Number of the specific outages caused by the induced atmospheric overvoltages (U_i) can be calculate starting from Rusck's formula [1]

$$U_i = 30 \cdot k_l \cdot I_t \cdot \frac{h_c}{b}, \quad (10)$$

where h_c is the average hanging height of phase conductors, b is the distance between striking point and line's axis, and k_l is a coefficient depending on the propagation speed of the backflash channel. Integrating (10) outside of the line's collecting area and if U_i = $U_{50\%}$, then results the specific number of outages at induced overvoltages

$$n_{oi} = \frac{6 \cdot A \cdot B \cdot D_l \cdot h_c \cdot P_a}{U_{50\%}} \cdot e^{-\frac{U_{50\% iz.LEA}}{10 \cdot B}}. \quad (11)$$

On the other hand, if there are not available registered data viewing the incidence of lightning strokes on line's corridor, to evaluate the number of lightings which affect power transmission lines, both at direct strokes and induced overvoltages, the following formula is good enough [7]

$$n_{lt} = 0{,}1 \cdot D_l \cdot \left(28 \cdot h_t^{0,6} + b_c\right), \qquad (12)$$

b_c representing line's corridor width. In this case, the total specific number of outages results from the formula

$$n_o = n_{lt} \cdot \left\{P_\alpha P_{fc} + (1\text{-}P_\alpha) \cdot \left[\gamma P_{ft} + (1\text{-}\gamma) P_{fgw}\right]\right\} . \qquad (13)$$

As a difference in comparison with formula (7), all the three components of specific number of outages refer only to the tower's height (h_t).

2.2. ATP MODEL OF THE POWER LINE

The aim of ATP simulation of transient due to direct lightning strokes in power lines is to analyze time evolution of voltages and to determine the protective currents, these values being inputs in number of outages calculation. The ATP model of the 400 kV analyzed line contains the following components:

- ⇒ two overhead line's spans and three towers;
- ⇒ two lines, at the sending end of the two spans, having such a length that the reflected waves from theirs ends do not affect the simulations` results;
- ⇒ the insulators of the three towers and modules that simulate the line's insulators flashover;
- ⇒ lightning pulse current generator.

The line between adjacent towers is modeled by four multi-phased nominal Π-equivalent circuits with distributed parameters. The Π circuits' are frequency independent and are calculated for 0,5 MHz, they are not transposed and the influence of corona discharge is neglected.

The extreme lines are modeled in the same way but they are long enough to avoid the influences of reflected waves at their receiving ends.

The propagation phenomena along the towers and their earthing grids involve equivalent circuits having distributed parameters. The authors' choice was to model the PAS type towers by mean of distributed parameters Π equivalent circuits. Each of such a circuit models the different parts of the metallic construction, as Fig.1 shows.

Tower's equivalent scheme is earthed through an R-L lumped parameters circuit, in this stage being not considered the earthing grid as a distributed one.

Line's insulators chains are modeled through their pulse capacity in association with modules that simulate the flashover, depending on the voltage-time insulators' characteristics. The pulse capacity of 400 kV insulators is about 140 pF and of 750 kV insulators is of 200 pF [1].

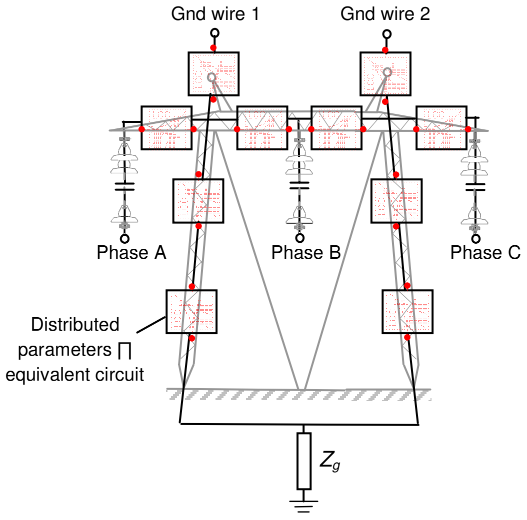

Fig.1. ATP model of a PAS type tower

The flashover arc is modeled by an R-L lumped parameters circuit, in this stage the dependence of the arc parameters by the current being neglected, because the aim of analysis is to determine protective currents.

A. Protective current estimation using *V-t* characteristic

The value of protective current when lightning strikes the power line's elements is determined after simulating the insulators' flashover. The models which simulate the flashover were realized in MODELS component of ATP program, on basis of following observation:

- When phase conductors or ground wires are stroked the shape of the overvoltage is quite similar to the lightning current's one, so the analysis involves normalized pulse voltage 1,2/50 µs. For this one, the insulator's voltage-time characteristic is given by the following formula:

$$V(t) = V_{50\%} \cdot \sqrt{1 + k_{iz} / t} \, , \qquad (14)$$

where k_{iz} constant depending on the nominal voltage of the line (k_{iz} = 3,41–for 400 kV). The time dependence given by (14) should be associated with a dispersion zone, ignored in this stage.

- When the top of a tower is stroked, the overvoltage waves have a short back, half-amplitude time being of 6÷8 µs. The behavior of insulators at short back pulses is not entirely known, some test on 110 kV lines' insulators showing an up to 50 % increase of flashover voltages, by report with that corresponding to the normalized pulse. An average increase of 38 % can be considered, both for positive and for negative pulses;

- At lower slops of the lightning current, the overvoltage has lower amplitude and the flashover time increases till 25 μs. However, the flashovers produced at bigger times then 6 μs are rare [8], so the protective current can be determined only for those flashovers that take place in maximum 6 μs from the beginning of the transient regime on the insulator (in concordance with J.G. Anderson's method);
- For power lines having nominal voltage higher then 220 kV, the operating voltage favors insulators' flashover. This is the reason why the potential of phase conductors is considered to be equal with the average value of operating voltage, for a half-period, and in opposite polarity with tower's potential;
- MODELS modules must initiate to generate voltage-time characteristic only when the insulators start to be stressed by the pulse voltage. So, these modules must considerate the propagation time from stroked point to tower.

B. Protective current estimation using LPM

Although leader progression models describe the final stage of the lightning discharge, the same principle can be used in order to study the insulators' flashover, as the leader begins its progress across the air gap, or the insulators' surface, when the voltage gradient exceeds a critical value E_0. As the leader develops across the insulators' surface, an increasing voltage is applied over the gap and the distance between the tip of the leader and the ground electrode decreases. For the uncovered gap, *x*, the voltage gradient increases along with the leader's velocity, *v*. As this process continues, the velocity of the leader increases until the leader reaches the ground electrode, at which time insulators flashover occurs.

The flashover process represented above is modeled by a single equation for the velocity of the leader. The CIGRE working group selected the following equation for analysis of the voltage across the line insulation [5]:

$$v = k_L V(t)\left[\frac{V(t)}{x} - E_0\right] \qquad (15)$$

Notation relation above have the following significance: *V(t)* is the voltage as a function of time, *x* is the distance of the uncovered gap, E_0 is the gradient at which the flashover process starts, and k_L is a constant, proposed by CIGRE.

A simple calculation algorithm, based on (15) can be implemented in order to determine the leader velocity at each time instant, estimating the new leader advancement for this time instant. Thus the following value of leader's length is obtained, and the new uncovered gap, *x*, can be determined if the insulators' length, *d*, is considered. At the time that leader covers the entire distance *d*, the insulators' flashover occurs.

Another ATP MODELS module was developed in order to simulate insulators' flashover according to leader progression methodology presented above. For different amplitudes of the lightning impulse wave, the flashover of the analyzed line insulators' is simulated. The lowest value of the lightning current which generates a voltage that leads to the insulators' flashover will be considered as protective current.

3. RESULTS AND COMMENTS

The analyzed line is a 400 kV overhead power transmission line realized on PAS towers and equipped with CTS 160-1 glass insulators. The length of the insulators is about 3230 mm, and the flashover voltage for negative lightning strokes is considered to be of 1792 kV. The phase conductors and ground wires sag is of 10 m and respectively of 8 m. The length between two adjacent towers is of 375 m.

3.1. LIGHTNING PROTECTIVE CURRENTS

When implementing the methodologies presented above and simulating the lightning direct strokes the following hypothesis must be considered:

A. Lightning strokes in phase conductors

In case of lightning strokes on phase conductors the external phases (A and C, Fig.1) are more likely to be hit, as they are less shielded by the ground wires.

When simulating the insulators' flashover both insulators' voltage-time characteristic and leader progression model approach were used, results being presented in table below:

Table 1

Results of strokes simulations in phase conductors

I [kA]	*V - t* Characteristic		LPM	
	U_{flash} [kV]	t_{flash} [μs]	U_{flash} [kV]	t_{flash} [μs]
8	2954	1.81	3943	2.27
6	2785	2.11	3467	2.75
4	2524	2.99	3346	3.71
3	2419	3.54	3084	4.61
2	2249	4.9	2992	6.52
1.5	2148	6.24	2751	7.98

The results are given for lightning strokes in the span's middle and for a 10 Ω towers' footing resistance. For lightning current smaller than 40 kA, the voltages induced on the healthy phases don't produce flashovers on their insulators.

As it can be observed from Table 1, the obtained values of protective current are slightly different for those two methods used, the LPM methodology reporting a bigger value than for the case of insulators'

V-t characteristic, 2 kA instead of 1.5 kA. At the same time flashover voltage and flashover time are larger for LPM than for insulators' *V-t* characteristic.

For the same lines' characteristics and without corona influence, formula (9) gives protective current of 3.5 kA.

B. Lightning strokes in line's towers

In this case the lightning is considered to strike the tower in its highest point, at the hanging point of the ground wires. When the tower is stroked only its insulators will flashover, and never the insulators of the adjacent ones.

When the lightning's current is near to the protective current flashovers only the insulator of the nearest phase, when the lightning's current increases flashovers the fare one and finally the insulator of the central phase. The results are given in table below:

Table 2

Results of strokes simulations in lines' towers

I [kA]	*V - t* Characteristic		LPM	
	U_{flash} [kV]	t_{flash} [μs]	U_{flash} [kV]	t_{flash} [μs]
340	3247	1.36	3505	1.56
320	3166	1.45	3473	1.7
300	3093	1.56	3430	1.85
280	3017	1.68	3388	2.02
260	2934	1.81	2093	2.28
240	2863	1.98	1713	2.52
233	2870	2.04	No flashover	

From Table 2 it can be observed that insulator's flashover occurs at a lower protective current when the insulators' *V-t* characteristic is used than in case of LPM approach. Thus the protective current was determined as 233 kA for *V-t* characteristic, and 240 kA for LPM, and the flashover voltage estimated with LPM is not greater for all the lightning current than that determined with the other method, as it was the case when lightning strikes the phase conductors (see Table 1).

Regarding the flashover time the LPM methodology reports a bigger time for insulators' flashover than the voltage-time characteristic approach.

In any case these values are higher than the normalized one (150 kA for VHV lines' towers) resulting so a better lines' behaviour on tower's direct strokes.

C. Lightning strokes in ground wires

When ground wires are stroked by lightning the obtained results are given in Table 3. Again those two methods propose different results as the protective current is of 183 kA when *V-t* characteristic is used and 186 kA when LPM is considered.

Analyzing results from Table 3, a relatively good correlation can be observed between the flashover voltage and flashover time reported by the methods.

Also it can be observed that for LPM results, the flashover voltage doesn't have a generally increasing trend as reported by the voltage-time characteristic.

Table 3

Results of strokes simulations in ground wires

I [kA]	*V - t* Characteristic		LPM	
	U_{flash} [kV]	t_{flash} [μs]	U_{flash} [kV]	t_{flash} [μs]
260	3486	1.1	3834	1.28
240	3383	1.19	3532	1.41
220	3270	1.3	2294	1.72
200	2363	3.9	2330	3.86
190	2384	4.01	1833	4.62
186	2120	6.7	2055	6.88
183	2119	6.74	No flashover	

As the voltage across the insulators' drops, the leader velocity also decreases and the advancement of the leader in this iteration will be smaller. Thus it can be explained the bigger flashover times reported by LPM than those obtained with the other method.

In the case of classic approach, the protection current corresponding to strokes in ground wires is twice then that of towers' striking.

As it can be observed from table above, the values of protection current obtained by simulation are smaller than that assumed by the classic approach, resulting so worst lines' performances than those corresponding to the classic approaches of specific number of outages.

These values have been obtained for a value of the grounding grid's resistance of 10 Ω and they are the same even one ground wire or both of them are stroked.

3.2. SPECIFIC NUMBER OF OUTAGES

After determining the values of the protective currents, the next step is to calculate the specific number of outages for the analyzed power line in the hypothesis considered above. This can be achieved by using the previously presented methodology.

Relation (3) is particularized and used for lightning strokes in phase conductors, line's towers and ground wires also considering the ground wires' fault shielding, P_α and the number of direct strokes on line's towers, γ, which were determined for the analyzed power line.

The obtained results are presented in Table 4 and as it can be observed when the specific number of outages is calculated using the protective current values determined with the *V-t* characteristic method and LPM method, quite similar results are obtained.

Table 4

Specific number of outages

Model	n_{od} [outages / 100 km and year] Lightning in:		
	Phase cond.	Towers	Gr. wires
Classic	0.175	0.354	0.087
V-t	0.176	0.105	0.300
LPM	0.176	0.114	0.313

The classical approach provide similar results only when the phase conductor is strucked by lightning, while in other cases different results are obtained.

These differences are imposed by the value of the protective current. In the classic approach the protection current is recommended by normatives and it its value is higher than those obtained by simulating, as previously determined.

Thus in case of direct strokes in line's towers the power line has a better performance if the protection currents obtained through simulation are consider, while in the other case when the ground wires are strucked by lightning the line's performance is worst for the simulated currents.

Anyway, the results obtained using the simulated values of the protective current are considered to be more realistic than those for the normalized currents due to the complexity of the models used in the simulation process.

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