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Implementation of the Analytical Method for the Lightning Performance Assessment of Power Line with Line Lightning Protection Devices

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***Abstract*—This paper presents the implementation of the analytical formula method to assess the lightning performance of OHL with Line Lightning Protection Devices (LLPD). The method is based on the classical representation of OHL and poles as an equivalent circuit to calculate a critical lightning current for flashover of the line insulation or LLPD and uses IEEE Std. 1410. The algorithm of automatic placement of LLPDs has been made to help engineers to install protective devices on power line maximally effective. The method has been tested on the line in Colombia.**

***Keywords*—lightning performance; OHL; outage; direct lightning strike; induced overvoltage; BFOR**

I. INTRODUCTION

At present, numerous methods of calculation of the lightning performance are available: with the use of the EMTP programs (ATPdraw, RV) [1, 2, 3, 4], 2D and 3D simulation in the FEM programs [5], by the Monte Carlo method [6], leader distribution model [7] and other. Most of them are labor-intensive, requiring competence in using specialized programs, and are individual for each specific line. These methods strive to describe the lightning phenomenon and its impact on the line as precisely as possible. As a result, this should demonstrate the annual number of outages of the specific line from lightning strikes. Practically, such accuracy is not important for the line operating companies, all the more so that the number of outages mostly depends on the lightning activity in the region that may change from year to year. The operating companies should know the way to increase the line lightning performance with the maximum efficiency and the minimum expenses without resort to complex calculations, composition of large line circuits and models.

The proposed analytical formula method implies a simplified approach to calculation of the number of annual line outages from direct lightning strikes (DLS) and induced overvoltages (IOV). It allows to evaluate the initial lightning performance of the line with no protective device quickly and with an acceptable accuracy, determining weak points along the line and offering an effective method to install the devices.

The proposed method is implemented in the Groza[TR] program where the protective devices from Streamer Electric Company are applied.

II. OUTAGES FROM DIRECT LIGHTNING STRIKE

In general, the total number of outages n_{tot} is composed of the outages from direct lightning strikes n_{dls} and induced overvoltages n_{iov}:

$$n_{tot} = n_{dls} + n_{iov} \tag{1}$$

The outages from direct lightning strikes on the line may be conditionally classified into 3 cases: strikes on the pole, strikes on the ground wire in the middle of the span and the shielding failure

$$n_{dls} = n_p + n_s + n_{sf} \tag{2}$$

where

n_p — number of outages from lightning strike on the pole

n_s — number of outages from lightning strike on the ground wire in the middle of the span

n_{sf} — number of outages from shielding failure

$$n_p = N_{dls}\, P_p\, P_{arc}\, P_{Ip}\, (1–Sf) \tag{3}$$

$$n_s = N_{dls}\, (1–P_p)\, P_{arc}\, P_{Is}\, (1–Sf) \tag{4}$$

$$n_{sf} = N_{dls}\, (1–P_p)\, P_{arc}\, P_{Ic}\, P_{sf}\, (1–Sf) \tag{5}$$

where

N_{dls} — the flash collection rate (flashes/100 km/yr)

P_p — probability of lightning strike on the pole

P_{arc} — probability of arcing

P_{sf} — probability of shielding failure

Sf — the environmental shielding factor, from 0 to 1

P_{Ip}, P_{Is}, P_{Ic},— probability of occurrence of the critical lightning current for the first flashover from strikes on the pole, on the ground wire in the middle of the span, and on the phase conductor from shielding failure

A. Flash collection rate

The number of DLS on the line is determined by the formula [8]:

$$N_{dls} = N_g \left(\frac{28h^{0.6} + b}{10} \right) \tag{6}$$

where

N_g — the ground flash density (flashes/km^2/year)

h — the average height of the line (m)

b — the width of the line (m)

B. *Probability of lightning strike on the pole*

The ratio of the number of lightning strikes on the pole with the long spans may be determined by the following formula [9, 10], but P_p should not exceed 0.5

$$0 < P_p = 4\frac{h_p}{l_s} \le 0{,}5 \tag{7}$$

where
h_p — the pole height (m)
l_s — the span length (m)

C. *Probability of arcing*

The probability of arcing is an important parameter for determination of the number of line outages. The capability to perform arc self-quenching will depend on the time the lightning strikes the phase. If the voltage is close to zero at this time, then the power arc may not occur due to a low voltage gradient along the flashed over path.

In case of a flashover in the string of insulators, the arcing probability may be evaluated by the following formula [9]:

$$P_{arc} = \left(1.6\frac{V_{line}}{l_{arc}} - 6\right)\cdot 10^{-2} \tag{8}$$

$$l_{arc} = d_{ins} + h_{ins}\, n_{ins} \tag{9}$$

where
V_{line} — the phase-to-ground voltage (kV)
l_{arc} — the span length (m)
d_{ins} — the insulator diameter (m)
h_{ins} — the structural height of one insulator (m)
n_{ins} — the number of insulators in string

If the protective devices with an increased quenching capacity are installed on the pole, then the probability of failure of the protective device is used instead of the arcing probability. Generally, this parameter may depend on the structural features of the device, the line voltage, the lightning current, and on the value of short-circuit in the fault location. For most LLPDs, the failure probability is about 0.03 - 0.05 [11].

$$P_{arc} = P_{fail}(V_{line}, I_{lihgtning}, I_{short}) \tag{10}$$

D. *Probability of shielding failure*

The probability of shielding failure when the lightning breaks through the ground wire depends on its geometrical arrangement with respect to the upper conductor. This probability for the lines up to 220 kV may be evaluated by the shielding angle of the wire [9].

$$P_{sf} = 10^{\frac{\alpha_{sh}\sqrt{h_{gw}}}{90}-4} \tag{11}$$

where
α_{sh} — the shielding angle (°)
h_{gw} — the average height of the ground wire (m)

E. *Probability of flashover*

The probability of flashover at the lightning strike on the line may be determined by the critical lightning current using the formula of distribution of the lightning currents from [8]. To solve this problem, the critical lightning current should be determined for the cases of strikes on the pole, on the ground wire in the middle of the span, and for the case of shielding failure.

$$P = \frac{1}{1+\left(\frac{I}{31}\right)^{2.6}} \tag{12}$$

F. *Self and mutual surge impedances*

All self-surge and mutual surge impedances of the conductors should be defined to calculate the coupling coefficients and the wave reflection coefficients.

Fig. 1 shows the coordinates of the conductors and ground wire in case of single -circuit line, conductor index is i = 0, 1… 3.

Self-surge impedance of the conductor i

$$Z_{ii} = 60\cdot\ln\frac{2y_i}{r_i} \tag{13}$$

where
r_i — radius of conductor i (m)

Mutual surge impedance between the conductor i and conductor j

$$Z_{ij} = 60\cdot\ln\frac{D_{ij}}{d_{ij}} \tag{14}$$

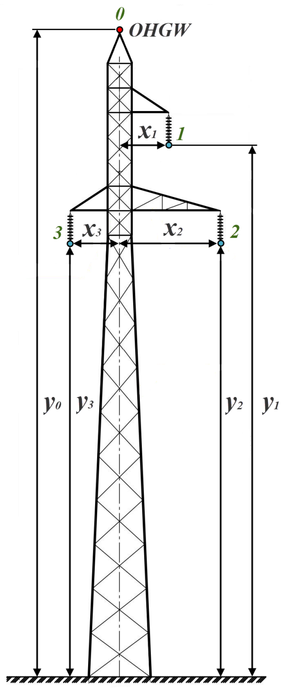

Fig. 1. Wire location coordinates for calculating surge impedances

where

D_{ij} — the distance between conductor i and image of conductor j (m), because $y_i >> x_i$ then

$$D_{ij} = y_i + y_j \tag{15}$$

d_{ij} — the distance between conductor i and conductor j (m)

$$d_{ij} = \sqrt{\left(x_j - x_i\right)^2 + \left(y_j - y_i\right)^2} \tag{16}$$

G. Reduction factor of lightning current

Let us consider the case of a lightning strike on a pole with a ground wire. It is interested in the current I_p, which flows through this pole. This current will be lower due to branching along the ground wire to adjacent poles. At that the shorter the span length is, the greater the current drain will be [12]. The current through the pole can be expressed in terms of the reduction factor $I_p=\eta\ I_L$. To determine the reduction factor, the equivalent circuit in Fig. 2 is used.

The electromagnetic wave is moving along the wire from the lightning strike location to the adjacent pole after $t=\tau_s=l_s/c$. The voltage of the reflected and refracted waves is determined using the reflection coefficient β and the refraction coefficient α:

$$\beta = \frac{\dfrac{Z_{00}R}{Z_{00}+R} - Z_{00}}{\dfrac{Z_{00}R}{Z_{00}+R} + Z_{00}};\ \alpha = 1+\beta \tag{17}$$

The wave reflected from the adjacent pole will reach the lightning strike location at $t=2l_s/c$, will be refracted with the coefficient α_1 and reflected again with the coefficient β_1:

$$\alpha_1 = \frac{2\dfrac{Z_L\cdot R}{Z_L+R}}{\dfrac{Z_L\cdot R}{Z_L+R} + \dfrac{Z_{00}}{2}};\ \beta_1 = \alpha_1 - 1 \tag{18}$$

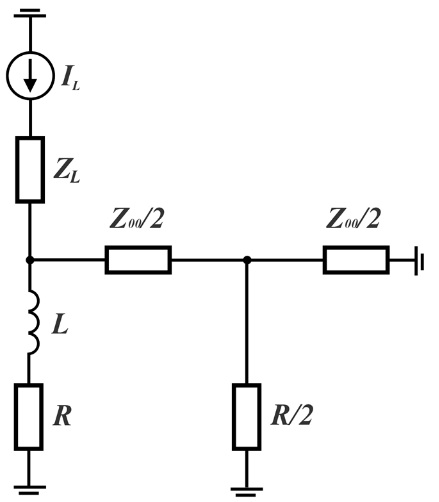

Fig. 2. Equivalent circuit for calculating the reduction factor of the lightning current

As time passes, more and more poles are engaged in the lightning current drainage to ground. For the actual values of lightning impulse front time and the footing resistance of the poles, the sufficient accuracy of calculations is ensured by consideration of reflections only from the adjacent poles nearest to the affected one. In this case, the factor of reduction of the current passing in the affected pole due to current drainage through the adjacent poles may be recorded as follows:

$$\eta = 1 + \frac{\alpha_1\beta}{1-\beta\beta_1}\left(1 - \frac{1-(\beta\beta_1)^n}{n\cdot(1-\beta\beta_1)}\right) \tag{19}$$

where n is the integral part of the ratio $t_f/2\tau_s$

H. Critical current to flashover

The next step consists in determination of the sequence of flashovers of all phases on the pole and searching for the critical lightning current for these flashovers. For the sake of simplicity, let us consider the case of a three-phase single-circuit line. The Roman numbers (I, II, III) will be used to designate the number of flashover in the following. The equivalent analytical model is shown in Fig. 3.

The equivalent footing resistance R^{eq} takes into account the lightning current drainage along the ground wire to the adjacent poles as it was stated in the previous, the lightning surge impedance Z_L=300 Ohm, as well as the voltage drop impact on inductance of the poles which is in inverse proportion to the lightning front time. As far as the conductors may be arranged at different heights, individual R^{eqI} is calculated for the first flashover for each conductor i:

$$R_i^{eqI} = \frac{\eta}{\dfrac{1}{Z_L} + \dfrac{1}{R_i^y} + \dfrac{2}{Z_{00}}} \tag{20}$$

$$R_i^y = R + \frac{y_i L_0}{t_f} \tag{21}$$

where

η — current reduction factor
Z_L — lightning surge impedance, (Ω)
R — footing resistance, (Ω)
L_0 — pole running inductance, (μH/m)
y_i — conductor suspension height, (m)
t_f — lightning impulse front time, (μs)

A potential from the ground wire should be induced on each conductor. This potential is determined using the coupling coefficient. To determine the first flashover, the coupling coefficient between the ground wire and the conductor i is calculated using the self-surge impedance of the wire and the mutual surge impedance of the conductor:

$$k_i^I = \frac{Z_{0i}}{Z_{00}} \tag{22}$$

After that, the critical lightning current is determined for the first flashover of each conductor i. V_{CFO} of the insulator or the protective device is used as a breakdown voltage:

$$I_i^I = \frac{V_{CFO\,i}}{R_i^{eqI}(1-k_i^I)} \tag{23}$$

The minimum positive current indicating the number of the phase where the first flashover will occur is selected from the values I^I_i:

$$I^I = \min\left(\left|I_i^I\right|\right), \tag{24}$$

The probability P^I of occurrence of the lightning current exceeding the critical value for the first flashover is determined by the formula (12).

Let us assume that the first flashed over phase is i=3 with the installed protective device (in this case, the number of the first flashover is $f1$=3). Provided that the LLPD has actuated correctly, the arc will be quenched and this will not result in the line outage. However, if other phases are not protected, the critical lightning current for the second flashover of the phases 1 or 2 should be determined to evaluate the number of probable outages. In the equivalent circuit Fig. 3, the first flashover is equivalent to the SW3 switch closing. The current will be partially drained along the conductor of the phase 3 and the equivalent resistance of the pole R^{eqII} will decrease. The coupling coefficient of the wire and the flashed over phase with regard to other phases will also change.

$$R_i^{eqII} = \frac{\eta}{\dfrac{1}{Z_L}+\dfrac{1}{R_i^y}+\dfrac{2}{Z_{00}}+\dfrac{2}{Z_{f1,f1}}};\quad k_i^{II} = \frac{Z_{0i}+Z_{f1,i}}{Z_{00}+Z_{0,f1}} \tag{25}$$

$$I_i^{II} = \frac{V_{CFO\,i}}{R_i^{eqII}(1-k_i^{II})};\quad I^{II} = \min\left(\left|I_i^{II}\right|\right) \tag{26}$$

The probability of the second flashover P^{II} is determined by the formula (12).

In such a way, the sequence of flashover on all conductors is determined step by step. In general, for every number of conductors i on the pole

$$R_i^{eqNf} = \frac{\eta}{\dfrac{1}{Z_L}+\dfrac{1}{R_i^y}+\dfrac{2}{Z_{00}}+\dfrac{2}{Z_{f1,f1}}+\ldots+\dfrac{2}{Z_{Nf-1,Nf-1}}}; \tag{27}$$

$$k_i^{Nf} = \frac{Z_{0i}+Z_{f1,i}+Z_{f2,i}+\ldots+Z_{Nf-1,i}}{Z_{00}+Z_{0,f1}+Z_{0,f2}+\ldots+Z_{0,Nf-1}} \tag{28}$$

$$I_i^{Nf} = \frac{V_{CFO\,i}}{R_i^{eqNf}(1-k_i^{Nf})};\, I^{Nf} = \min\left(\left|I_i^{Nf}\right|\right) \tag{29}$$

$$P^{Nf} = \frac{1}{1+\left(\dfrac{I^{Nf}}{31}\right)^{2.6}} \tag{30}$$

where

Nf — number of flashover from 1 to i

$f1, f2$ ...— number of the first, second, etc. flashed over conductor.

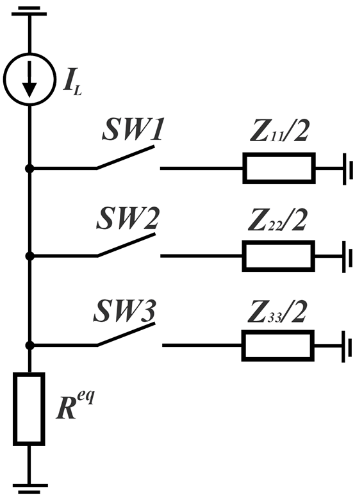

Fig. 3. Equivalent circuit for calculating the flashover sequence

III. Outages from Induced Overvoltages

The calculation of the number of outages from induced overvoltages is simplified as in the case with direct lightning strikes. Using the results of the numerical computation from the IEEE Std. 1410 (obtained by Borghetti in [13], Fig. 4) one approximation formula may be noted for resistivity up to 1000 Ωm

$$n_{iov} = 15 h_{eff} P_{arc} e^{-\frac{V_{CFO}}{2.5\cdot h_{eff}}} \tag{31}$$

where

P_{arc} — probability of the arcing

h_{eff} — effective height of the conductor above ground which considers the soil resistivity and may be determined by the formula [8]:

$$h_{eff} = h + 0.25\sqrt{\rho} \tag{32}$$

ρ — soil resistivity, (Ωm)

h — average height of the conductor above ground, (m)

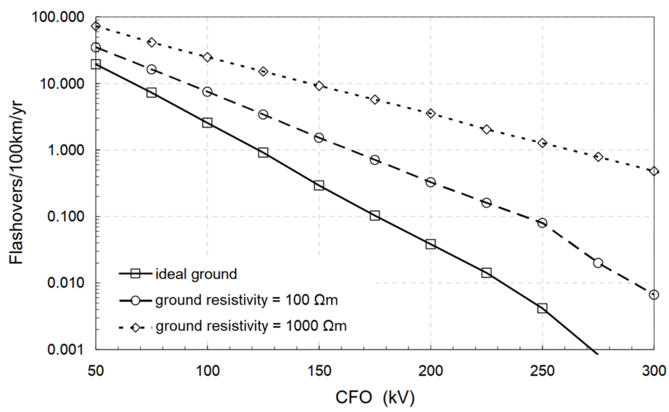

Fig. 4. Number of induced-voltage flashovers versus distribution-line insulation level, from IEEE Std. 1410

IV. ALGORITHM OF EFFICIENT ARRANGEMENT OF PROTECTIVE DEVICES

In order to protect the line against lightning in an optimum way, the weakest part of the specific line should be defined. In practice, the line may always be divided into areas or sections depending on footing resistance, structure of the poles, shielding factors, type of insulation, and other.

For each designated section, the number of outages with no installed protective devices is calculated, as well as the number of outages with one, two or three installed LLPDs per pole. The proposed algorithm ranks the line sections and the number of protective devices to achieve the minimum total number of outages.

As an example, let us assume that the initial single-circuit line consists of 3 sections. The matrix n_{si} of 12 values of outages per 100 km should be calculated then (Table I.), where $s = 1\ldots 3$ – index of the sections, $i = 0, 1 \ldots 3$ – index of the number of protective devices per pole.

After that, an intermediate effectiveness parameter is calculated for each case.

$$E_{si} = \frac{n_{si}}{n_{\max}} l_s \tag{33}$$

where
n_{max}=max(n_{si}) — maximum value of the matrix n_{si}
l_s — span length of the section s

Then the increment of the effectiveness parameter is calculated for the cases with the installed protective devices.

$$\Delta E_{si} = \frac{E_{s0} - E_{si}}{i} \text{ for } i = 1, 2, 3 \tag{34}$$

The maximum increment of the effectiveness parameter ΔE for the whole matrix is indicative of the sought cell with the index s and i to which the first rank is assigned. This means that when installing the protective devices in the line being considered, the fitter should start with the section s^I and install i^I number of protective devices on each pole.

$$\Delta E_{s^I i^I} = \max(\Delta E_{si}) \rightarrow s^I, i^I \tag{35}$$

Let us assume that all poles of the section s^I were equipped with i^I number of protective devices. In order to determine the next section for protection of the rank *II*, the same algorithm is applied, however, ΔE should be recalculated for the section s^I:

TABLE I. OUTAGE MATRIX

Protection	*Section 1*	*Section 2*	*Section 3*
Initial	n_{10}	n_{20}	n_{30}
1 LLPD	n_{11}	n_{21}	n_{31}
2 LLPD	n_{12}	n_{22}	n_{32}
3 LLPD	n_{13}	n_{23}	n_{33}

$$\Delta E_{s^I i} = \begin{cases} \dfrac{E_{s^I i^I} - E_{s^I i}}{i - i^I} & \text{for } i > i^I \\ 0 & \text{for } i \le i^I \end{cases} \tag{36}$$

After recalculation of the increment of the effectiveness parameter for the section s^I, the next cell in rank is selected by the maximum ΔE of the whole matrix

$$\Delta E_{s^{II} i^{II}} = \max(\Delta E_{si}) \rightarrow s^{II}, i^{II} \tag{37}$$

In such a way, the sections and the number of necessary protective devices may be ranked starting from the "weakest" cell to the "strongest" one along the entire line.

V. METHOD IMPLEMENTATION

The described method was implemented in the software package Groza for calculation of the line lightning performance. The Groza software allows simulating a single-circuit line or a double-circuit line up to 115 kV divided into sections in order to determine the lightning protection level of each line section with/without the protective devices.

Line voltage, geometrical arrangement of all conductors and wires, pole configuration and type, line insulation, and lightning activity in the region are specified as input parameters for calculation.

The results define the annual number of line outages from direct lightning strikes and from induced overvoltages.

The algorithm to determine the arrangement of the protective devices is used in two versions:

- In case of the limited availability of the LLPDs, the program arranges all devices in an efficient way to achieve the minimum number of outages.
- In order to reach the necessary number of line outages, the program selects the sufficient number of devices and arranges them optimally.

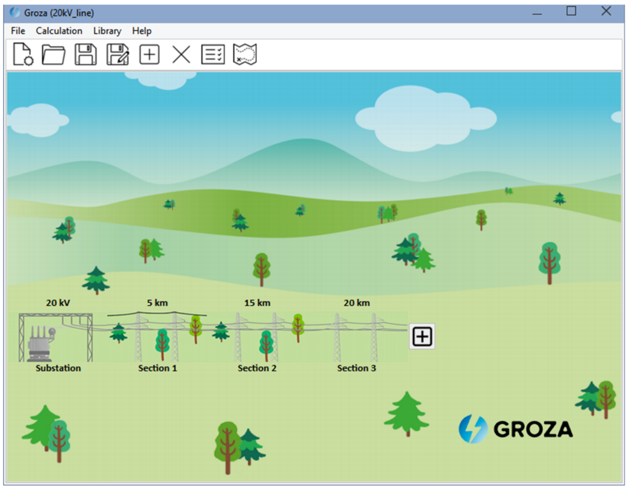

Fig. 5. Groza software interface

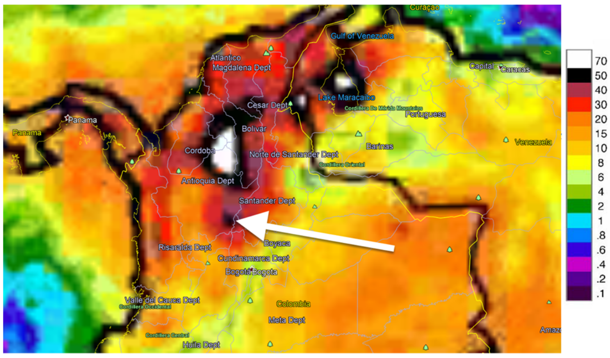

Fig. 6. GFD in installation region

VI. Practical implementation

In January 2018 the Groza software was used to determine the most vulnerable sections of a distribution power line and to design a most efficient way of lightning protection device deployment scheme for this particular line. The 13,8 kV line is located in Colombia in a region with one of the highest lightning flash density rate in the world (Fig. 6), in particular during the year 2017 there were observed 38 outages resulted by lightning on this particular 30 km line .

In accordance with software recommendations obtained after analysis of line segment data, ten poles of the line were equipped with DLS LLPDs and 62 poles were equipped with IOV LLPD, in total the protected area have reached 17% of line length. One year later results of LLPD implementation were analyzed - number of lightning outages occurred on the line in 2018 was compared with those of 2017 (one year before installation vs one year after installation). Event timestamps of circuit breaker operation were compared with those of regional lightning monitoring system in order to define if lightning was a reason of fault current establishment and further circuit breaker operation. All circuit breaker events, that had a timestamp equal to lightning event were considered to be triggered by lightning. Finally, a following improvement of line reliability performance was observed.

There is an insignificant deviation between results of analytic approach and real statistics (Table II), which is caused by the fact that lightning as an extremely uneven phenomenon. However, obtained results already prove that chosen analytic model is applicable for three specific purposes demanded by distribution grid operators, such as determination of most vulnerable line segments, designing of most efficient schemes of lightning protection equipment deployment and evaluation of financial efficiency of the project.

TABLE II. OUTAGE QUANTITY

	Total outages	***By lightning***	***Percentage***
2017	102	38	37%
2018	43	1	2,3%
GROZA forecast w/o LLPD	n/a	41	n/a
GROZA forecast with LLPD	n/a	3	n/a

VII. Conclusion

A simplified method for calculation of the lightning performance of power transmission lines was presented. This method is based on an analytical formula method where a minimum set of input parameters of the line and the region is required to solve the final problem. The method contains formulas for determination of the annual number of outages from direct lightning strikes and induced overvoltages. This approach may be easily used to evaluate an increase in the line lightning protection level with installation of protective devices and to find an optimum arrangement of the devices on the poles. The method is simple and useful for line design engineers and for operating companies.

The method of ranking of line sections depending on their weakness to overvoltages from lightning is described. This method allows to define efficiently the minimum number of protective devices to reach the maximum lightning protection level of the initial line.

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