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Determination of Cumulative Distribution Function of the Crest Value of the Lightning Current Flowing Through Line Surge Arresters

SUMMARY

For the selection and design of line surge arresters (LSA), it is essential to know the characteristics of the lightning current circulating through LSA. When lightning strikes a transmission line, only a part of the lightning current circulates through LSA.

This part mostly depends on the point of impact, and the characteristic of the lightning strike current. The determination of the cumulative distribution function of the lightning current circulating through arresters is presented in first part of the paper. It can be applied on transmission lines where LSAs will be installed to protect the line against the effect of atmospheric discharges.

Second part of paper presents the calculation results of the cumulative distribution function of the lightning current circulating through arresters for particular 110 kV transmission line located in an area with high lightning activity.

KEYWORDS

atmospheric discharges, line surge arresters, cumulative distribution function, lightning current, lightning strike, EMTP, LIPS.

INTRODUCTION

1.1 Line surge arresters

The main task of a transmission system operator is the establishment of an energy supply infrastructure in order to maintain security of supply with minimal costs and environmental protection. Energy transmission is performed by a transmission network including overhead lines that are exposed to a various factors from external environment. One of them is lightning strike, also known as a natural "transient" phenomenon, which can potentially be cause for outages of transmission and distribution lines.

Nowadays the lightning phenomenon is well explored and elaborated, but is still necessary to perform a lot of research for its full understanding. Line surge arresters (LSAs) are installed on overhead transmission lines to improve its Line Lightning Performance (LLP), by reduction of the number of outages and as a consequence for increasing reliability of the entire transmission system.

1.2 Application of LSAs on 110 kV overhead transmission line Ston - Komolac

The 110 kV overhead transmission line Ston - Komolac (with interpolated SS Rudine) is a 44 km long single circuit shielded line located in the mountainous region near Dubrovnik with a high lightning activity (the keraunic level is about 70 thunder days per year). Since it was considered that this line

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had a bad lightning performance [1], the Croatian Transmission System Operator (HOPS) has started a pilot project to install line surge arresters in 2007 (Figure 1a), in order to improve the overvoltage protection, lightning performance and consequently the reliability of this line. The current configuration consists of 104 LSAs installed as follows: 50 towers with 1 LSA installed in bottom phase, 24 towers with 2 LSAs installed, one in lower and one in middle phase, and 2 towers with 3 LSAs installed, one at each of the bottom, middle and top phase. In 2008, 2 real-time measurement systems (RMS) are installed on transmission line towers no. 38 and 110 in 2009. A RMSs includes the following components: a solar power supply, a controller, an acquisition unit and a communication system. RMS (Figure 1b) has a sensor for measuring the transient current flowing through the ground conductor of the top phase LSA and a specifically developed Rogowski coil that has been installed around the tower in order to measure the total lightning current flowing through it.

a)

b)

Figure 1: a) Part of 110 kV overhead transmission line Ston - Komolac with installed LSAs, b) LSA and real-time measurement system installed on tower no. 38.

Due to the effective selection of the LSAs it is important to know the characteristics of the lightning currents circulating through LSA. The paper shows a theoretical evaluation of the crest value of the lightning current circulating in a line arrester, and the probability followed by this variable. Calculations were performed with the software EMTP-RV and LIPS (Lightning Impact on Power Systems), which is toolbox based on EMTP (DCG version) devoted to the calculation of the failure rate of apparatus due to lightning, and covers direct and induced lightning.

FORMULATION OF THE PROBLEM

It is assumed that four different types of points of impact-will be considered: tower, shield wire, phase conductor and adjacent towers. The probability of having a lightning current circulating in the arrester with a crest (peak) value , higher than a given value can be determined based on the statistics of lightning strikes on the observed transmission line. Let us denote by the current circulating in the arrester that we consider, and let us characterize a lightning strike event by the following set of random variables:

- *I* the crest value of lightning strike current;
- *X* the point of impact along the transmission line.

Then I_a is a function *h* of I and X, as follows:

$$I_a=h(I,X) \quad (1)$$

The probability of having a current circulating in the LSA higher than the value is given by the following integral estimated from equation (1):

$$P(I_a>i_0)=P(h(I,X)>i_0)=\iint_{\{h(x,i)>i\_0\}} f_{(X,I)}(x,i)dxdi \quad (2)$$

where $f_{(X,I)}$ is the joint probability density function of the random variables (I,X). Let us note that $P(I_a>i_0)=1-F(I_a)\ (i_0)$, where $F(I_a)\ (i_0)$ is the cumulative probability distribution of , that cumulative function can be calculated as follows:

$$F_{(I/X=j)}\ (.)=p(I_a<i_0)=\int_0 i^0 fI_a\ (i)di \tag{3}$$

In order to simplify the problem, the point of impact of the lightning strikes along the line X is considered in the following part of the paper as a discrete random variable whose values are a set (X_i). Let us note that $f_{(I/X=j)}\ (.)$ is the probability density function of the lightning strike current given that the point of impact is X_i. As indicated previously, it is assumed that three different types of impacts are used (strikes on tower, shield wire and on phase conductor). $p_X\ (x=X_i)$ is the probability of having a lightning strike of point of impact X_i. With these variables defined, the probability from equation (2) can be expressed as follows using the Bayes' law:

$$P(I_a > i_0) = \iint_{\{h(x,i)>i_0\}} p_x(x=1) f_{I/X=1}(x,i)dI + \iint_{\{h(x,i)>i_0\}} p_x(x=2) f_{I/X=2}(x,i)dI + \cdots = p_x(x=1) \iint_{\{h(x,i)>i_0\}} f_{I/X=1}dI + p_x(x=2) \iint_{\{h(x,i)>i_0\}} f_{I/X=2}dI + \cdots \tag{4}$$

The cumulative distribution function (CDF) means the probability that the real variable I_a be equal or lower than value I_o. Therefore, as the problem is formulated to have a lightning current circulating through the LSA I_a higher than the value I_o, the complementary cumulative distribution function is used, as follows:

$$1 - F_a(i_0) = p_x(x=1)\left[1 - F_{I/X=1}(I_1)\right] + p_x(x=2)\left[1 - F_{I/X=2}(I_2)\right] + \cdots \tag{5}$$

or

$$F_a(i_0) = p_x(x=1)\left[F_{I/X=1}(I_1)\right] + p_x(x=2)\left[F_{I/X=2}(I_2)\right] + \cdots \tag{6}$$

Where $F_a\ (.)$ is the cumulative distribution function of the crest value of the current circulating in the arrester, $F_{(I/X=j)}\ (.)$ is the cumulative distribution function of the lightning current, given that the point of impact is j as presented in equation (3), and I_j is the lightning current for the point of impact j, such as $h(I_j,j)=i_0$ (see paragraph 2). The determination of the cumulative distribution function is made based on equation (6) and involves four successive steps:

- **Step 1**: determination of the probability density function of the crest value of the lightning strike current at ground level $(0\text{-}I_{max})$;
- **Step 2**: determination of the probability of the crest current of the lightning strikes at a given point of impact along the line (based on the notion of attractive surfaces [3]);
- **Step 3**: determination of the probability of having a lightning strike impacting the different elements of the line considered $p_x\ (x=X_i)$;
- **Step 4**: estimation of the probability $P(I_a>i_0)$ from the previous step.

The details of this approach are presented in the next chapter.

CUMULATIVE DISTRIBUTION FUNCTION (CDF)

3.1. Step 1

In the first step, the probability density function of having a lightning strike current in the range $0\text{-}I_{max}$, where I_{max} is the upper value of the lightning striking the ground, is determined numerically from the lightning statistics of [4],[5]. In this paper we consider only negative downward lightning strikes because they represent in Europe 90 % of the total lightning strikes. The crest value of the first strike lightning current can be considered lognormally distributed, but the parameters of the log-normal distribution presented in [5] have to be modified in order to take into account that this distribution corresponds to measurements on towers [6] and not on the ground. The general equation of the probability density function, of a lognormally distributed random variable (in this equation is the value of the lightning crest current) is:

$$f_I(.) = \frac{1}{\sqrt{2\pi}\beta I} e^{\frac{-1}{2}\left(\frac{ln(I/M)}{\beta}\right)^2} \tag{7}$$

where M is the median value, and β is the logarithmic standard deviation.

The probability for lightning striking the ground and towers are not similar because of the Electro-Geometric Model (EGM) [7]. The probability for lightning striking on ground was determined numerically, based on a Monte-Carlo method [8][9].

3.2. Step 2

In the second step, the determination of the probability of the crest current of the lightning strikes at a given point of impact along the line was performed using attractive surfaces deduced from the application of the EGM [7]. EGM concepts imply that points of impact and lightning crest currents are correlated random variables. The EGM is a technique used to calculate the average annual number of lightning striking on the different elements of an overhead line and also the attractive surfaces of the different point of impacts [11]. The EGM model we have used was a classical one and it was based on the method presented in [5], [17]. The model of Love was used. For each point of impact one can numerically obtain the conditional probability density function of the lightning crest current for a given point of impact. As illustration, Figure 2 shows a simplified application of the EGM for a given lightning current. The lightning leaders supposed to come vertically from the cloud lead to a lightning strike on the shield wire if their trajectory has an intersection with the segment (*A,B*), otherwise they hit earth.

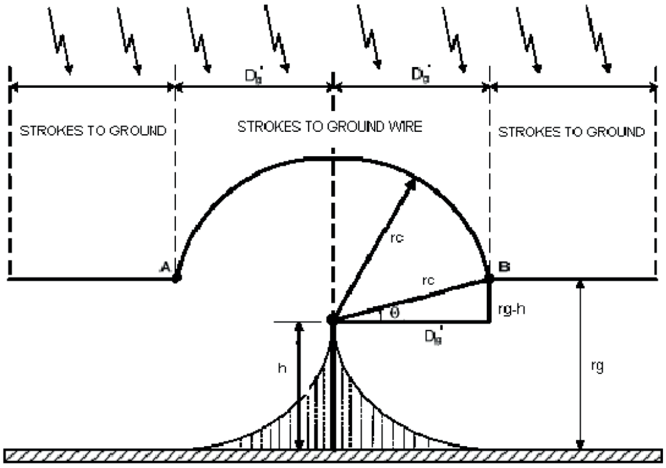

Figure 2: Electro-geometric model of a single ground wire [10].

As explained before, we have considered that the point of impact X_i is a discret random variable with only three possible positions, considering that the line is geometrically uniform:

- tower;
- shield wire;
- phase conductor.

The conditional probability density function of the crest current at the point of impact is given by the following equation:

$$f_{I/X=X_i}(.) = \frac{f_I(i)S(x,i)}{\int_0^\infty f_I(j)S(x,j)dj} \tag{8}$$

where is the probability density function of the crest current on the ground, is the attractive surface for the considered point of impact . is a function of the lightning strike current and the point of impact, has been calculated in the previous step. The values of the attractive surface are taken from the EMTP-RV toolbox LIPS, according to the application of the EGM [9] for different values of in the range 0-200 kA. The denominator of the right term of (8) is approximated as:

$$\int_0^\infty f_X(j)S(x_j,j)dj \approx \sum_0^\infty f_X(j)S(x,j) \tag{9}$$

The integral from equation (9) corresponds to the total number of lightning strikes striking , with a ground flash density equal to 1.

3.3. Step 3

As it noted in Step 2, three possible positions are considered for the point of impact: strikes to tower, shield wire and phase conductors. In order to determine the probability of having a lightning strike on the different points of impacts, some simulations with the toolbox LIPS were performed). LIPS includes a 3D EGM and is able to launch automatically EMTP-RV to calculate the flashover rate of overhead lines and the risk of failure of transmission apparatuses due to lightning [11]. LIPS's simulation results give us from the ground flash density and the structure of the line the average annual number of strikes per year and per element (tower, shield wire, phase conductors, adjacent tower). The annual number of strikes per year on the towers, adjacent to the observed tower, is taken into account, but lightning strikes on the towers and the span located after these two towers are not considered because it was proven with EMTP-RV simulations that these lightning strikes generate very low transient currents through the arresters of the observed tower. Figure 3 below shows the annual number of strikes per year on the affected elements.

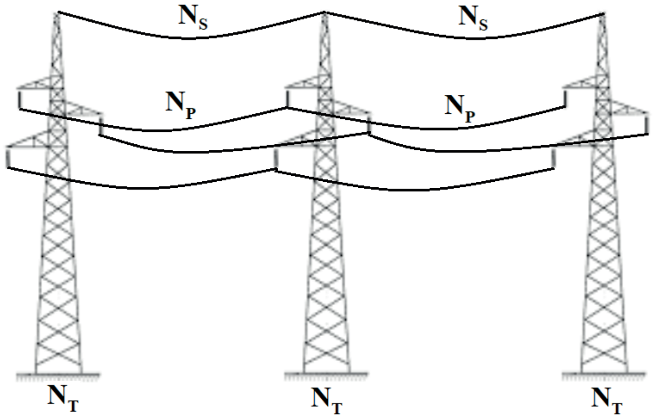

Figure 3: The annual number of strikes per year on the affected elements (tower 2 is the observed tower, tower 1 and 3 are respectively the left and right adjacent towers).

On Figure 3, N_t is the average annual number of strikes on the tower (equal for each tower), N_s is the average annual number of strikes on the shield wire (for one span) and N_p is the average annual number of strikes on the phase conductors (for one span). N_{total} is the total annual number of strikes on each element of the portion of the transmission line considered, its value can be calculated as follows:

$$N_{total}=3N_t+2N_s+2N_p \qquad (10)$$

The general equation for calculating the probability of having a lightning strike impacting the line on the element X_i can be calculated as follows:

$$p_x(x = X_i) = \frac{N_i}{N_{total}} \qquad (11)$$

where N_i is the annual number of strikes on the striken element of transmission line, total N is the total annual number of strikes on all the elements considered in the calculation. Consequently, the probability of having a lightning strike on the tower where the measurement system is installed can be calculated as follows:

$$p_x(x = observed\_tower) = \frac{N_T}{N_{total}} \qquad (12)$$

The probability of having a lightning strike on the shield wire is:

$$p_x(x = shield\_wire) = \frac{2N_S}{N_{total}} \qquad (13)$$

The probability of having a lightning strike on the phase conductor is:

$$p_x(x = phase\_conductor) = \frac{2N_P}{N_{total}} \qquad (14)$$

The probability of having a lightning strike on one adjacent tower is:

$$p_x(x = adjacent\_tower\ ) = \frac{2N_T}{N_{total}} \qquad (15)$$

3.4. Step 4

In step 4, the probability of the lightning crest current $P(I_a>i_0)$, described in step 2 is estimated. Practically, for a set of values (I,X) it is possible to determine numerically with the software EMTP-RV the function h, using a limited number of simulations per point of impact considered. The modelling of the system follows the recommendations of [14], [15].

The lightning current amplitudes used in the simulations are in a range from $0\text{-}I_{max}$ (0-200 kA) in order to determine a lightning strike currents I, stroking the transmission line and leading to a current in the arrester $0\text{-}I_a$, with a crest value higher than i_o. The simulations results were stored in a database, which allows to put into relation the values of the lightning strike currents in a range $0\text{-}I_{max}$ with the corresponding currents that circulates through the LSA in a range $0\text{-}I_{a\_max}$. All parameters that are necessary to solve equation (6) are known from the previous steps, except the cumulative distribution functions $F_{I/X=j}$, which can be estimated as follows. With a step of 1 kA, we determine the value of the lighting currents which causes a current circulating through the LSA of value I_a. Then, from the values of the lightning currents determined with the calculations performed in step 2, one selects the corresponding values of the CDF function $F_{I/X=j}$. With this approach, all parameters that are required in order to solve equation (6) are known.

APPLICATION ON A SPECIFIC 110 kV TRANSMISSION LINE

This chapter shows the results of the calculations from step 1 to 4, for the crest value of the lightning current circulating in an arrester of the 110 kV transmission line Ston-Komolac [13]. This transmission line was chosen for calculations because route of the line is located in an area of high lightning activity and had a large annual number of outages. In order to protect against lightning, the mentioned transmission line was also equipped with LSAs, and consequently is an interesting application case of the method presented in this paper. The statistical data from [1], [2] and [12] shows how LSAs installation can significantly improve its operational reliability and its LLP. The term "*observed tower*", that was previously mentioned in this paper, refers to the tower where the monitoring system for measuring the lightning current circulating in arresters is installed [13].

4.1. Results of Step 1

The probability density function of the crest value of the lightning strike current on the ground level in the range $0\text{-}I_{max}$ is determined in the 1st step, which parameters are presented in Table 1. It is assumed that $0\text{-}I_{max}$ is 200 kA.

Table 1: Parameters of the log-normal distribution of the lightning current, lightning striking the ground according to [4],[5]..

	< 20 kA	> 20 kA
β	1,33	0,605
M	36,2	26,2

4.2. Results of Step 2

The conditional probability density function of the lightning crest current given the point of impact as well as the attractive surfaces expressed in m² versus the lightning current are calculated in step 2. The calculation was performed according to equation (8). Values marked with yellow in Table 3 are expressed in percentage and mean probability density function of having a lightning strike with a crest value ; the corresponding attractive surface is indicated. For example, the density of probability that a lightning strike of 1 kA terminates on the observed tower is very low, particularly 0,00017 % with an attractive surface corresponding to this current of 100 m²; the density of probability for the shield wire is 0.0059 % (with an attractive surface of 3900 m²).

Table 2: Probability density function of the crest current at the different points of impact, and the attractive surfaces expressed in [m²] (abbreviations: t.-tower, s.w.-shielding wire and p.c.-phase conductor).

I [kA]	$S(x{=}t.,i)$	$S(x{=}s.w.,i)$	$S(x{=}p.c.,i)$	$f_{I/X=X_i}(t.)$	$f_{I/X=X_i}(s.w.)$	$f_{I/X=X_i}(p.c.)$
1	100	3900	1360	0,000174	0,005937	56,072057
25	4928	18004	0	0,004354	0,292610	0
50	9740	19994	0	0,008709	0,578333	0
75	14060	20268	0	0,013063	0,834842	0
100	18096	19968	0	0,017418	1,074488	0
125	21876	19348	0	0,021772	1,298933	0
150	25376	18600	0	0,026127	1,506753	0
175	28744	17720	0	0,030481	1,706735	0
200	31896	16832	0	0,034836	1,893892	0

4.3. Results of Step 3

In 3rd step, the results are calculated with the toolbox EMTP-LIPS. These results include the annual number of strikes per year and per element (the observed tower, adjacent towers, shield wire and phase conductors).

$$p_x\ (x{=}\text{observed\_tower}){=}0{,}096$$

$$p_x\ (x{=}\text{shield\_wire}){=}0{,}7044$$

$$p_x\ (x{=}\text{phase\_conductor}){=}0{,}0061$$

$$p_x\ (x{=}\text{adjacent\_tower}){=}0{,}1929$$

The influence of both adjacent towers from the observed one is taken into account (symmetrical to the observed tower). The highest probability for lightning to strike the shield wire (70,44 %). The probability to have a lightning strike impacting the phase conductor is the lowest (0,61 %).

4.4. Results of Step 4

These results includes:

The set of values $I_a{=}h(I{,}X)$ which gives the value of the lightning strike current I, striking the transmission line at a given point of impact X, which will be at the origin of a current in the arrester of value I_a.

The set of values $F_{I/X=j}$ versus I.

The model of tower with air gaps used for EMTP-RV simulations is presented on Figure 4.

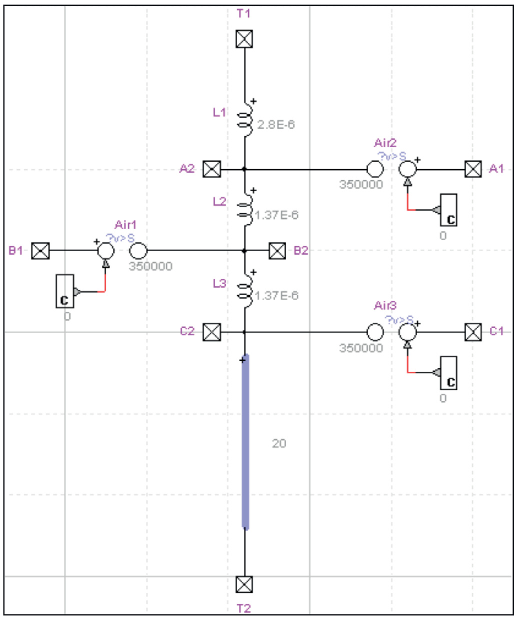

Figure 4: Model of tower with air gaps used for EMTP-RV simulations [13].

Figures 5, 6, 7 and 8 present a part of the EMTP-RV simulation results. They are used for the determination of the value of the lighting strike current I, striking the transmission line at a given point of impact, which causes a current in the arrester of a value I_a (it is considered that a lightning strike with higher lightning current leads to a current in the arrester higher than I_a). The set of values of the current I_a in the arrester versus the current I of a lightning strike at a given point of impact is presented below (based on data from Table 3).

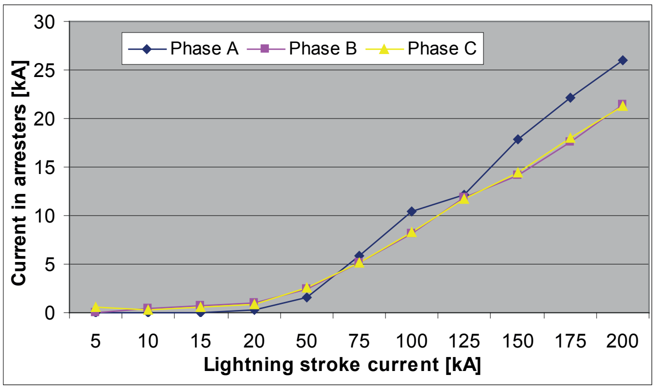

Figure 5: Current in the arrester versus lightning current for a strike at the observed tower.

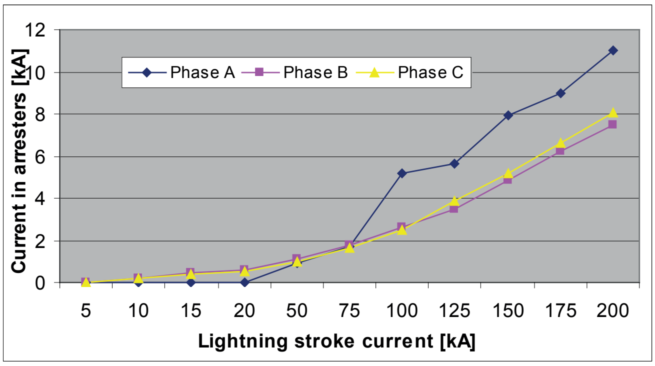

Figure 6: Current in the arrester versus lightning current for a strike at the shield wire.

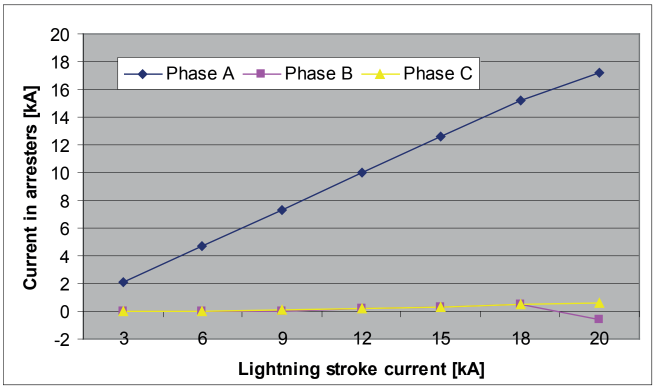

Figure 7: Current in the arrester versus lightning strike current for a lightning stroke on phase A.

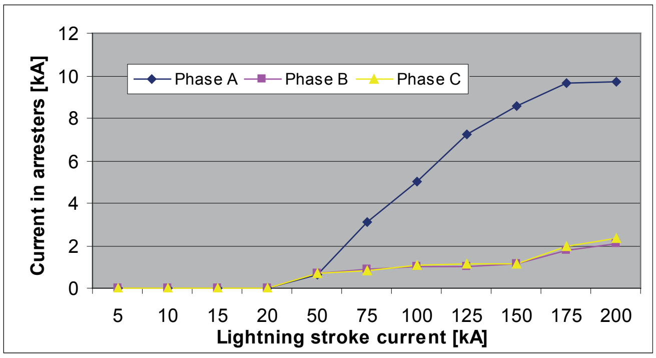

Figure 8: Current in the arrester versus lightning stroke current for a strike on an adjacent tower.

Table 3: Results of the cumulative distribution function calculated for a current circulating in the arrester in the range 0-25 kA, for different points of impact

(abbreviations: t.-tower, s.w.-shielding wire and p.c.-phase conductor, a.t.-adjacent tower).

I_a [kA]	I [kA]	$F_{I/X=t.}$	I [kA]	$F_{I/X=s.w.}$	I [kA]	$F_{I/X=p.c.}$	I [kA]	$F_{I/X=a.t.}$
0	0	0	0	0	0	0	0	0
1	20	0,1093	50	0,8346	2	0,4109	55	0,7357
2	40	0,5306	75	0,953	4	0,8825	60	0,7824
3	60	0,7824	70	0,94	5	0,9506	73	0,8684
4	70	0,8523	85	0,9708	7	0,9987	88	0,9253
5	77	0,887	130	0,996	8	1	100	0,9521
6	80	0,8991	135	0,9965	10	1	110	0,9668
7	85	0,9164	140	0,9974	0	1	112	0,9691
8	90	0,9307	150	0,9982	0	1	144	0,9905
9	97	0,9465	175	0,9995	0	1	155	0,9938
10	100	0,9484	180	0,9996	0	1	179	0,9981
11	112	0,9691	200	1	0	1	200	1
12	125	0,9793	0	1	0	1	0	1
13	130	0,9827	0	1	0	1	0	1
14	135	0,9856	0	1	0	1	0	1
15	140	0,9889	0	1	0	1	0	1
16	145	0,9908	0	1	0	1	0	1
17	150	0,9925	0	1	0	1	0	1
18	160	0,995	0	1	0	1	0	1
19	165	0,996	0	1	0	1	0	1
20	170	0,9969	0	1	0	1	0	1
21	172	0,9972	0	1	0	1	0	1
22	175	0,9973	0	1	0	1	0	1
23	185	0,9985	0	1	0	1	0	1
24	190	0,9992	0	1	0	1	0	1
25	200	1	0	1	0	1	0	1

In Table 3, I_a is the value of current circulating in the arrester, I is the corresponding crest value of the lightning strike current and $F_{I/X=j.}$ is the cumulative distribution function of the lightning current, given that the point of impact is (tower, shield wire, phase conductor and adjacent tower). Figure 10 shows (the CDF of the arrester crest current, given that lightning strikes the observed tower) that the mean value of the current is approximately about 3 kA, which means a 50 % probability considering that lightning strikes the observed tower, and causes a current circulating in the LSA higher than 3 kA. But the probability to have a current circulating in a line arrester I_a higher than 10 kA is approximately 5 %, and the probability to have a lightning current circulating in the line arrester I_a higher than 20 kA is neglectable, therefore 20 kA corresponds to the upper limit of the current circulating in the LSA, in the given case.

A part of calculation results for total CDF in the range of 0-25 kA is shown in Table 4.

Table 4: Total CDF, in the range 0-25 kA.

I [kA]	$F_a(i_0)$
0	0
1	0,7430
2	0,8697
3	0,9202
4	0,9507
5	0,9770
6	0,9814
7	0,9841
8	0,9902
9	0,9933
10	0,9944
11	0,9970
12	0,9980
13	0,9983
14	0,9986
15	0,9989
16	0,9991
17	0,9992
18	0,9995
19	0,9996
20	0,9997
21	0,9997
22	0,9997
23	0,9998
24	0,9999
25	0,9999

The CDFs of a lightning current circulating in the LSA, estimated with equation (6), taking into account the different points of impact, are shown on Figures 9-12. The analyze of figures 9 -12 leads to the following conclusions: the CDF of the current in the LSA given that lightning strikes the observed tower shows a 1% probability to lead to a transient current circulating in a LSA higher than 16 kA, while the case when lightning strikes the phase conductor A shows a 1% probability to lead to a lightning current circulating in the LSA higher than 6 kA (this is due to the protection against lightning provided by the shield wire).

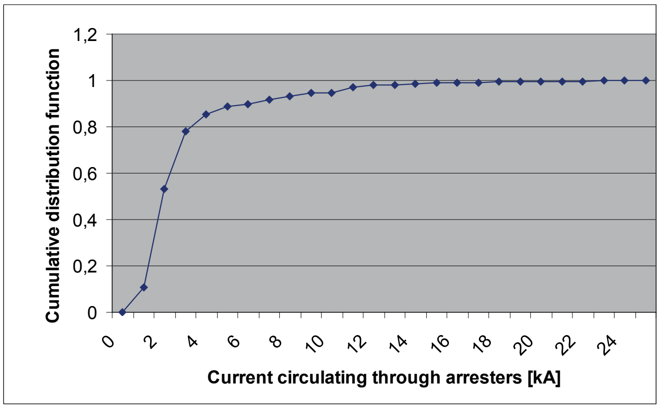

Figure 9: CDF of the current in arrester given that lightning strikes the tower where the measurement system is installed.

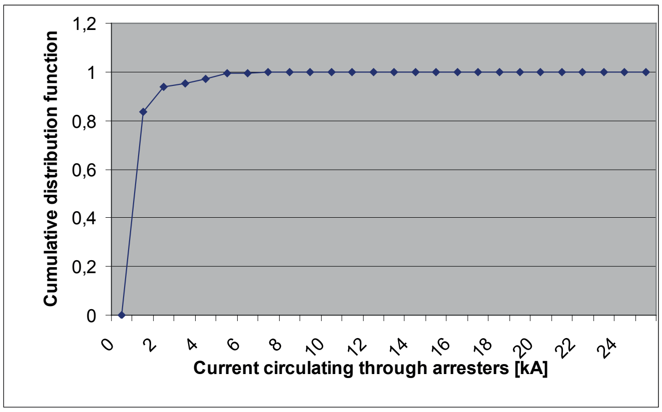

Figure 10: CDF of the current in arrester given that lightning strikes the shield wire.

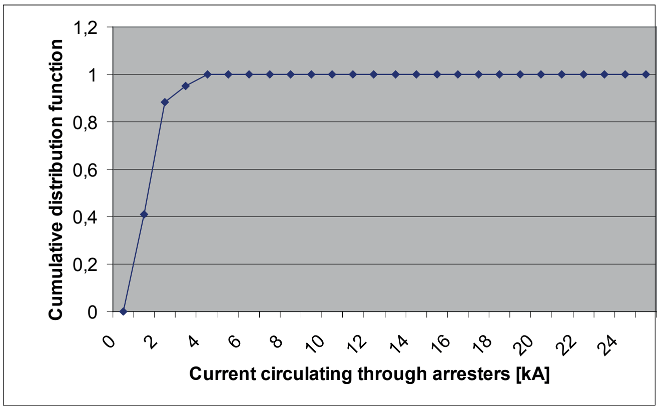

Figure 11: CDF of the current in arrester given that lightning strikes the phase conductor A.

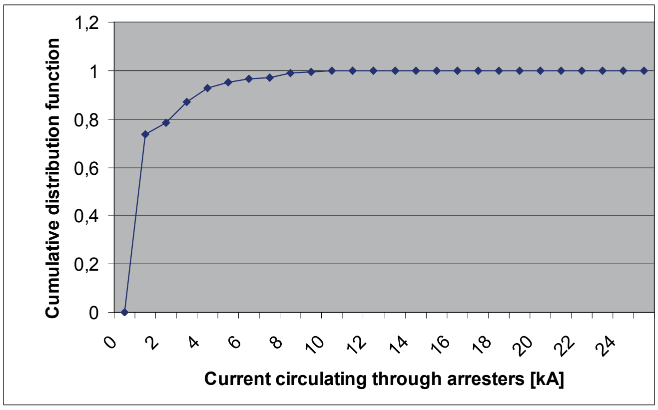

Figure 12: CDF of the current in arrester given that lightning strikes the adjacent tower.

Figure 13 shows the total CDF of the lightning current in the arrester. With EMTP-RV simulations it is determined that lightning strike currents in the range 0-200 kA, will cause currents circulating in the arrester in the range 0-25 kA. The median value (50 %) of the current circulating through the arrester is 2 kA. This total cumulative distribution function shows that the probability to have a current circulating in LSA higher than 10 kA is 1%.

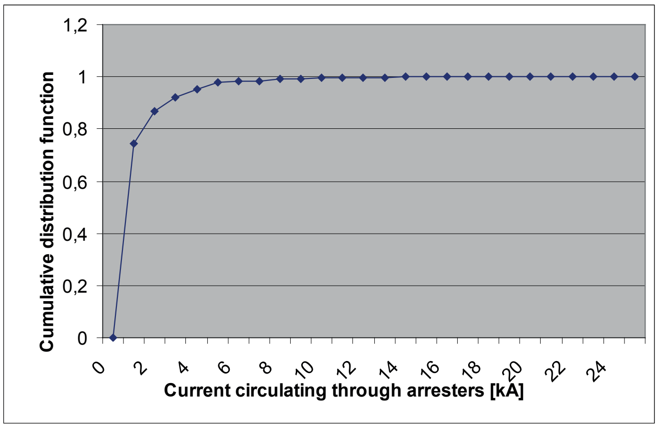

Figure 13: Total CDF of the lightning current through the arrester of the observed tower.

CONCLUSION

The determination of the cumulative distribution function of the lightning current circulating in LSAs is presented in this paper, and it can be applied for any transmission line, where LSAs are installed [17]. In order to simplify the problem, the following points of impact on the transmission line 110 kV Ston-Komolac were considered: the observed tower (no. 38 where the lightning real time measurement system is installed), both adjacent towers, the shield wire and the phase conductors of both adjacent towers. Through 4 successive steps, by using the software program EMTP-RV [18], and the configuration with data of the transmission line 110 kV Ston-Komolac (structure of towers, footing resistances, characteristics of LSAs installed on the line etc.) it was possible to estimate the cumulative distribution function of the lightning current circulating through a LSA which give us the probability for a lightning current circulating through LSA I_a, with a crest value higher than value i_0.

This function can be useful for the selection and design of LSAs which will be installed on transmission lines to avoid outages due to lightning. Generally, the simulation results indicates, that the lightning strikes in the range 0-200 kA will cause currents thorough a LSAs in the range 0-25 kA, with the highest contribution from lightning striking the shield wire. It is important to note that these conclusions are done for a line with a shield wire. The application of the method on a line without shield wire would have led to other conclusions [16]. We should highlight also that a method similar to the one presented in this paper could be used to evaluate the energy constraints applied to LSAs.

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