Optimal Line Surge Arresters Installation Using Lightning Location System

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Abstract – *The paper presents a methodology for the reduction of the number of lightning flashovers on a 220 kV double-circuit line. From the geometry of the line and the ground-flash density it is possible to calculate the number of flashovers. The procedure for the calculation of flashovers includes three steps: application of an electro-geometric model, simulation of the electromagnetic transients due to lightning strokes and evaluation of the flashover rate. The models of the elements used in the calculation are presented: lightning stroke current, tower, conductors, insulator string, line surge arrester (LSA) and tower footing resistance. The case study of a 220 kV double-circuit overhead line is conducted in order to improve its lightning performance. Different mitigation measures on a line for prevention of flashovers could be applied and one of the most effective means is the installation of LSAs. The best solution depends on the number of LSAs, their location and their price. Data from Lightning location system (LLS) can also help for the choice of towers for LSA installation. Calculations are conducted using the software EMTP-RV and LIPS.*

***Keywords**: Line surge arresters, lightning location system, 220 kV double-circuit line, modeling, EMTP-RV, flashover, lightning performance*

Nomenclature

A, B, C	Phases
a	Constant [3.3 – 10.6]
b	Constant [0.5 – 0.85]
DE	Detection efficiency of LLS
DA/LA	Detection/location accuracy of LLS
E_0	Soil ionization gradient
EMTP-RV	Simulation software
I	Lightning current amplitude, Stroke current through the resistance
I_g	Limiting current to initiate sufficient soil ionization
k, U_0,DE	Constants
LSA	Line surge arrester
LIPS	Simulation software
LLS	Lightning location system
LINET	One lightning location system
P	Probability of occurrence of a lightning current
R, R_i	Tower footing resistances
R_o	Footing resistance at low current and low frequency, i.e. 50 Hz
S_m	Current steepness
T_0	Time from which $U(\tau) > U_0$
TPP	Thermo power plant
$U(\tau)$	Voltage applied at time t, to the terminals of the air gap
U_0	Minimum voltage to be exceeded before any breakdown process can start or continue
Z	Tower surge impedance

I. Introduction

The transmission line faults caused by lightning can be classified into back-flashovers and flashovers due to shielding failures. The back-flashovers on the insulator string may involve one or more phases and one or more circuits of a double-circuit line. Reduction of the tower footing resistance is the traditional solution to reduce the number of back-flashovers (i.e. flashovers due to lightning striking towers and shielding wires). To avoid back-flashovers due to lightning strokes to tower or overhead shielding wires, the tower footing resistance should be as low as possible. In some areas where the soil resistivity is high, this method is too costly to be really of practical interest [1].

Let us add also that a solution, sometimes used for suppression of double-circuit simultaneous faults, consists of installing an unbalanced insulation on a double-circuit line [2], [3], but this solution does not change the total number of flashovers. In other aspects, increasing the number of shielding wires or grounding wires is practically almost impossible on existing transmission lines.

These traditional countermeasures are often not effective enough to prevent simultaneous faults and therefore the installation of LSA can be helpful in such cases in order to prevent double-circuit outages.

In this way power supply continuity will be secured and the flashover rate of the double-circuit line significantly improved.

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Experience shows that the use of LSAs is more efficient than the conventional methods listed above, especially in cases of double-circuit faults of transmission lines, which can be eliminated almost completely with LSAs [4].

There are many references [5]-[17], which deal with different aspects of LSA installation on transmission and distribution lines, but to find the most effective ways to reduce the number of double-circuit faults with the minimal number of LSA is still a challenge. Data from LLS can help for the choice of towers for optimal LSA installation.

The case study presented in this paper is related to the improvement of the lightning performance of a 220 kV double-circuit overhead line, which connects a thermo power plant (TPP) to the rest of the power system, [18]. Several double-circuit outages caused the interruption of the power supply of the TPP and it was necessary to understand the origins and prevent such outages. Therefore calculation results for different line configurations, without and with LSAs, were compared.

II. Data from LLS

For more than 30 years, in most countries, data from LLS have been used for different purposes. There are many different LLSs used in the world and some countries are covered with two, three or more different LLS [19]. The main quality parameters of each LLS are: detection efficiency (DE) map and detection/location accuracy (DA/LA) map for monitored territory. It is clear that better LLS has better DE and better DA/LA. Various statistical analyses can be conducted with many years of lightning data collection. Map of medium lightning density for monitored territory is one of these analyses. If lightning density map is high resolution, e.g. 1x1 km^2, it is possible to determine lightning density for each transmission line tower location.

For the 220 kV double-circuit overhead line considered, the lightning density (N/km^2/year) at each tower position is shown on Fig. 1. Lightning density on the right axis is quite high because LINET LLS counts each stroke in lightning flashes. It is clear that lightning location data should be for a long time period (as many years as possible) because lightning activities vary with period of the day, month, season and year.

Lightning density is not the biggest on maximum altitude of double-circuit lines, as it could be expected, Fig. 1. Double-circuit line from tower 75 to TPP is the most exposed to lightning flashes. Towers with the largest footing resistance and the highest lightning density should be chosen for optimal LSA installation.

More generally, the following procedure, which will be explained in detail through the case study that follows, is suggested, for optimal LSA installation (Fig. 2).

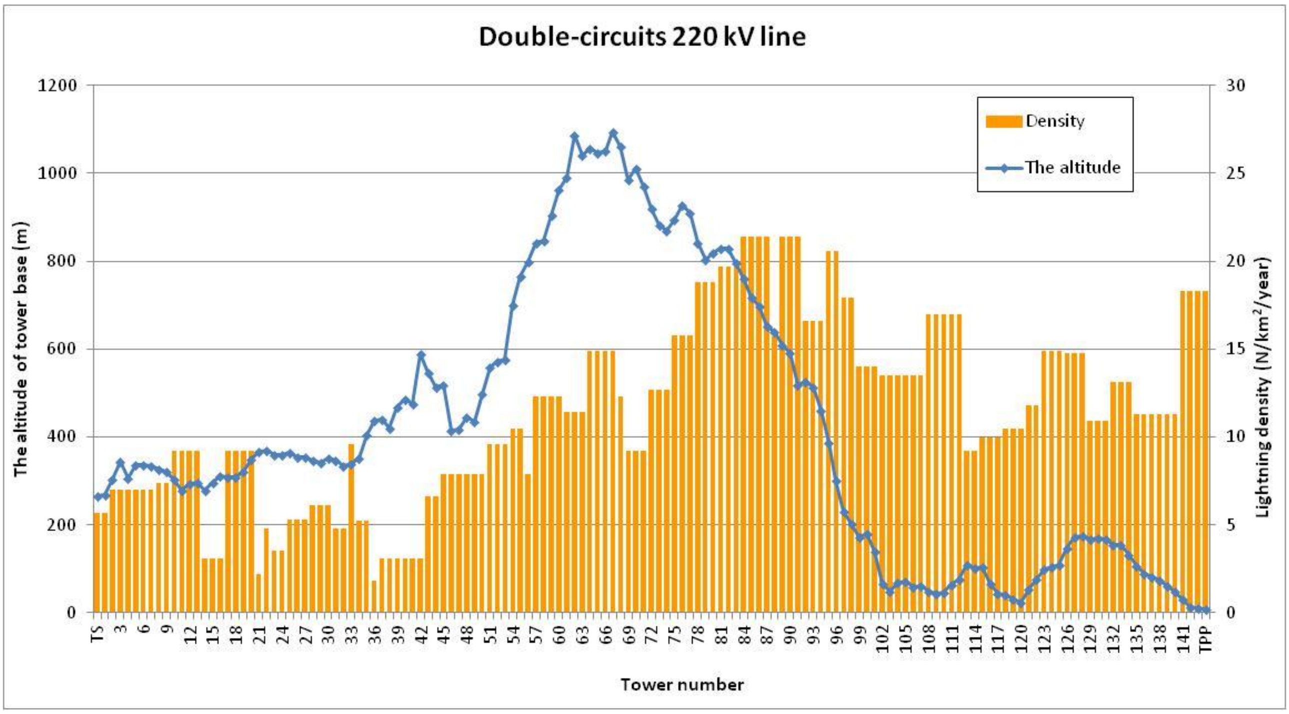

Fig. 1. The altitude of tower and lightning density (N/km^2/year) on tower position

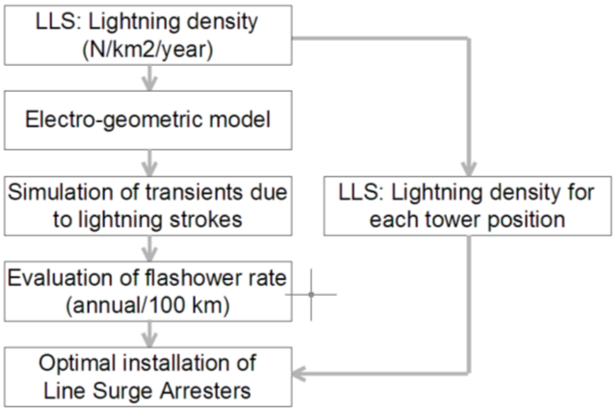

Fig. 2. Procedure for optimal installation of LSA

III. Simulation of Lightning Strokes Impacting the Transmission Line

Lightning strokes impacting the HV transmission line are observed in order to determine the density of lightning strokes, which quantifies the threat of lightning strokes per unit length of a line. The average lighting stroke density for a given area is defined as the number of strokes per unit area during a long time period.

The goal of the simulation is to determine the distribution of lightning current amplitudes which strike HV transmission line towers and shield wires or the phase conductors directly. Furthermore, characteristic values, such as minimal, maximal and critical current amplitudes will be determined. The Monte Carlo method is used; in the case considered here, this method consists in reproducing numerically a stochastic problem. An important set of lightning strokes is chosen according to the probability followed by the basic stochastic variables, then the effect of each of these lightning strokes is determined numerically. This method allows avoiding difficult integral calculations, especially when the range of the integral is huge and when the frontier of the domain in which the integral is to be calculated is difficult to determine. By a large number of simulations it is possible to calculate relevant values which are statistically arranged and are later used in lightning overvoltage calculation.

The basic variables needed for simulation are the variables defining the trajectory of the lightning stroke from the cloud and the lightning current amplitude, for which the statistical distribution is known. The log-normal distribution, which is mostly used [20], can be approximated as following:

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

Where:

I - lightning current amplitude (kA),

P - probability of occurrence of a lightning current amplitude higher than *I*.

The above distribution is adopted to represent the distribution of peak-current amplitudes for negative downward flashes in the normal range of structure heights, [21] and [22].

It should be mentioned that data from LINET LLS suggests that the number 31 kA in equation (1) is too high.

The general expression for the striking distance is represented by the equation:

$$R = a \cdot I^{b} \qquad (2)$$

Where:

R - striking distance,

I - lightning current amplitude,

a - constant [3.3 – 10.6],

b - constant [0.5 – 0.85].

Different values of parameters and modifications of the above equation are proposed by various investigators [3], [20]. Some authors suggest different values of constants for striking distance to ground and for striking distance to phase conductors or shielding wires. In the calculations presented in this paper the expression above has been used with *a*=7.2, *b*=0.65.

The tower of a double-circuit 220 kV line and part of a transmission line is depicted in Fig. 3. Shielding wire and phase conductors of both circuits are modeled up to four spans on both sides from the point of impact.

In order to collect enough data for statistical calculation, the simulation is conducted for a large number of generated lightning current amplitudes. The random nature of lightning phenomena can be quantified with a large number of samples that make more credible results of statistical calculation. Hence, simulations with a large number of strikes are made first in order to get a better view of the numerical relations between ground strikes, strikes on shielding wires and towers and phase conductor strikes.

Calculations were carried out until 1000 simulations resulted in phase conductor strokes. There were a total of 37932 simulations conducted, of which 25635 resulted in ground strikes, 11297 in shielding wire and tower strikes. According to statistical calculation, the following characteristics of the crest values of the current for lightning striking phase conductors are calculated:

- average value: 15.40 kA,
- medium value: 13.82 kA,
- variance: 98.36 kA,
- standard deviation: 9.92 kA,
- maximal phase conductor stroke current: 42.80 kA,
- critical current: 47.30 kA.

Critical current (i.e. maximal lightning stroke current which could strike the phase conductor according to electro-geometric model) is calculated for the highest conductor on the tower of the observed part of the transmission line. According to the simulation results 8.85% of total lightning strokes resulted in shielding failure – the distribution is shown in Fig. 4. This confirms a well known fact that an overhead line with a single shielding wire is only poorly protected from a direct lightning strike and therefore the current of a lightning stroke that can hit a phase conductor can be of high magnitude.

Fig. 4 depicts the distribution of lightning currents striking phase conductors and Fig. 5 the distribution of currents hitting the top of towers or shielding wire.

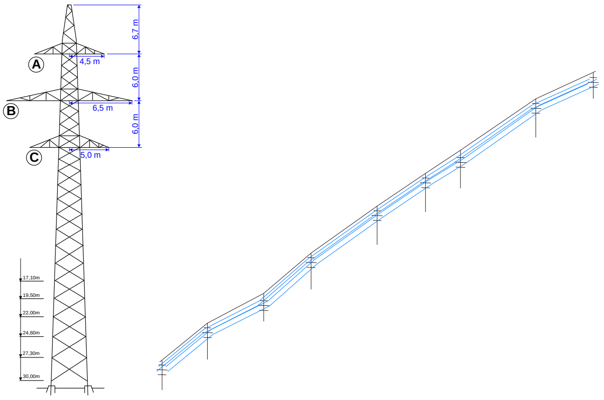

Fig. 3. 3D model of the part of the studied transmission line between towers 62 and 70.

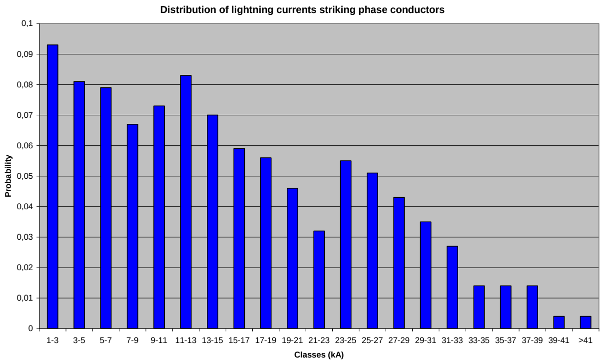

Fig. 4. Distribution of lightning currents striking phase conductors

The distribution of lightning strokes per phase shows that 66.18 % of strokes, striking phase conductors finished in the upper phases. About 32.35% of lightning strokes finished in middle phases and about 1.47% of lightning strokes, which striking the lower phases, cannot lead to a flashover (e.g. 2.56 kA, 3.06 kA).

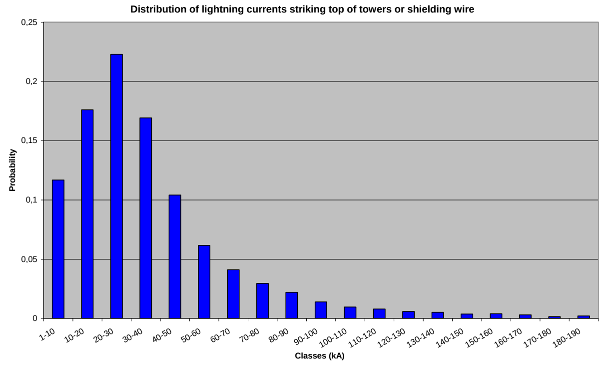

Fig. 5. Distribution of lightning currents striking top of towers or shielding wire

IV. Modeling Procedure for Transient Simulation

In the case study a 220 kV double-circuit line with one shielding wire is modeled.

The lightning stroke hitting a tower or a phase conductor can be replaced by a surge current generator and a resistor (Norton generator). The peak current magnitude and the tail time are important when observing the arrester energy stresses [23], while the influence of the rise time is hardly noticeable in such a case. In contrast the current wave front is an important parameter with regard to insulator flashover. The CIGRE Lightning Current Waveform model [21] can approximate the concave form of the lightning current front.

The transmission line, conductors and earth wire are represented by several multi-phase untransposed distributed parameter line spans at both sides of the point of the lightning stroke impact. Four line spans at both sides of the point of impact are modeled in observing the flashovers of the insulators. To avoid reflection of traveling waves, 10 km of line are connected at both ends. Fig. 6 depicts the model used for simulation of lightning striking a double-circuit 220 kV line.

Tower surge impedances [24] are calculated using equation (3). Each tower is divided in four parts. First part is from tower top to upper arm, second one from upper arm to middle arm, third part from middle arm to lower arm and the last part from lower arm to ground. That way it is possible to calculate the transient voltages of tower arms.

$$Z = 60 \cdot \left\{ \ln\left(\frac{H}{R}\right) - 1 \right\} \qquad (R << H) \qquad (3)$$

Phase voltages at the instant at which a lightning stroke impacts the line must be included.

The largest voltage difference across insulator/arrester terminals occurs during the peak value of phase voltage, which has the opposite polarity of the lightning surge. **Insulators** themselves represent capacitances with only very moderate influence on the occurrence of overvoltage. The decisive parameter for the behavior of overhead line insulation subjected to lightning overvoltages is its corresponding flashover voltage, which depends on the voltage level due to different insulation clearances. The area criterion involves determining the instant of breakdown using the equation (4).

$$Integrate(t) = \int_{T_0}^{t} \left(U(\tau) - U_0\right)^k d\tau \qquad (4)$$

where:

U(τ) is the voltage applied at time t, to the terminals of the air gap,

U_0 is a minimum voltage to be exceeded before any breakdown process can start or continue,

k and U_0 and DE are constants corresponding to an air gap configuration and overvoltage polarity,

T_0 is the time from which $U(\tau) > U_0$,

U_0, *k* and DE are determined by using the voltage-time curve and the basic impulse insulation level (BIL) of 1050 kV. The values of the parameters used are:

U_0 = 958 kV, k = 1, DE = 0.3805718.

Flashover occurs when Integrate(t) becomes equal to DE (constant).

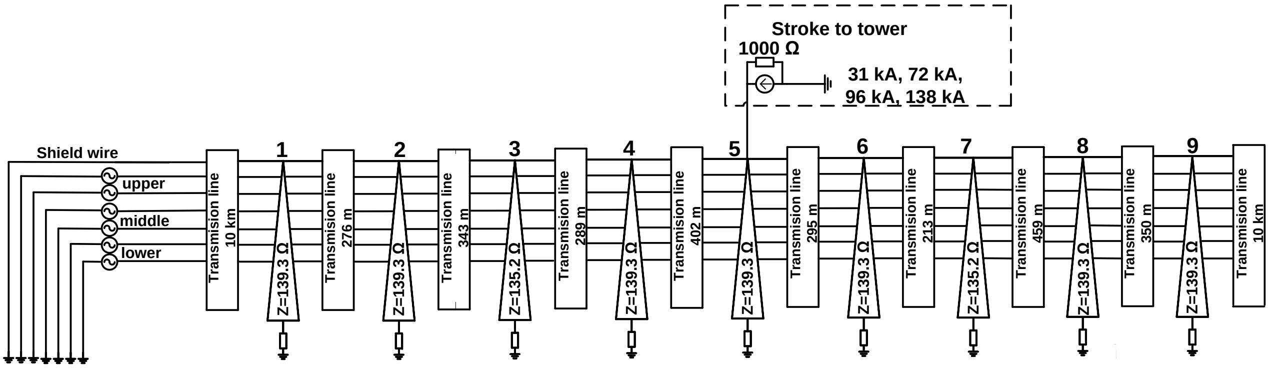

Fig. 6. Model of 220 kV double-circuit line

Tower footing resistances are modeled taking ionization into account [25], [26]. The ionization model according to equation (5) takes into account the soil ionization that is caused by the lightning currents. In the EMTP, calculation the tower grounding is represented as a non-linear resistor (Fig. 7):

$$R_i = \frac{R_o}{\sqrt{1+\left(\frac{I}{I_g}\right)}} \qquad (6)$$

Where:

R_o - footing resistance at low current and low frequency, i.e. 50 Hz [Ω],

I - stroke current through the resistance [kA],

I_g - limiting current to initiate sufficient soil ionization [kA].

The tower footing resistance remains $R_i = R_o$ if $I < I_g$ and varies according to the given equation if $I > I_g$. The limiting current is given by:

$$I_g = \frac{\rho \cdot E_0}{2 \cdot \pi \cdot R_o^2} \qquad (6)$$

Where:

ρ - soil resistivity [Ωm];

E_0 - soil ionization gradient, recommended value: 400 [kV/m].

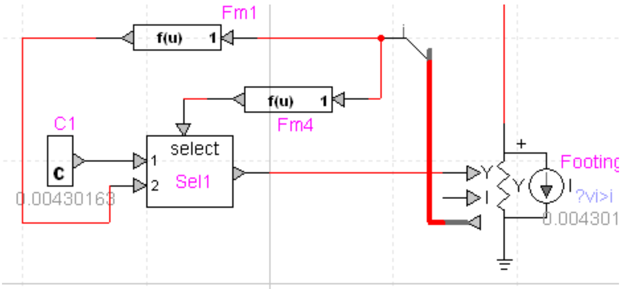

Fig. 7. EMTP-RV Model of footing resistance ionization [27]

The model of gapless type LSA includes non-linear and dynamic behavior of the arrester. The non-linear behavior is represented by the U-I characteristic depicted in Fig. 8.

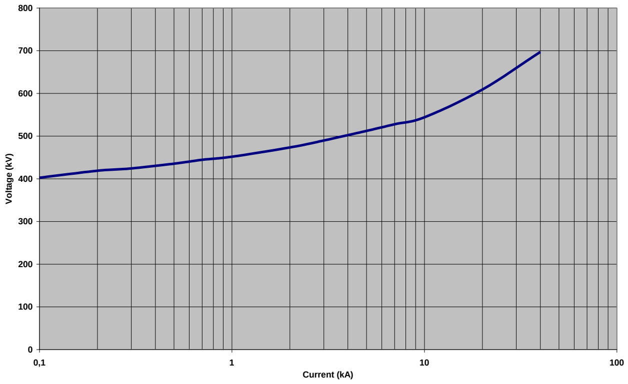

Fig. 8. U-I characteristic of surge arrester for the 220 kV line (U_r=210 kV)

V. Simulation Results

When a lightning strikes the top of a 220 kV tower the occurrence of the back-flashover depends on many parameters such as: peak current magnitude and maximal steepness, tower footing resistance, flashover voltage of insulation clearances, magnitude and phase angle of the phase voltage, atmospheric condition (rain, snow, pressure, temperature, humidity) etc.

The main aim of the study conducted was the prevention of double-circuit simultaneous outages due to lightning by installing LSAs in only one circuit. Back-flashovers are only considered because the intention was to maintain at least the continuity of service of one circuit. Shielding failures were not specially studied as they could not cause simultaneous outages of both circuits. The results presented are related to one circuit of the double-circuit line.

Table I shows results of simulation for different tower footing resistances and peak current magnitudes that could be exceeded in 50%, 20%, 10%, 5% and 2% of cases, according to equation (1). The green color indicates that back-flashover will not occur in any phase and for any combinations of phase angles of phase voltages. The grey color indicates the dependence of back-flashover on the phase angle of the voltage. Back-flashovers that occur at least in one phase of the circuit, independently of the phase angle of the voltage, are marked with the red color in Table I.

TABLE I
BACK-FLASHOVERS IN RELATION TO THE LIGHTNING CURRENT MAGNITUDE AND THE FOOTING RESISTANCE OF A TOWER

ρ (Ωm)	R (Ω)	P(31 kA) = 50% S_m=25.78 kA/μs	P(52.8 kA) = 20% S_m=34.56 kA/μs	P(72 kA) = 10% S_m=40.98 kA/μs	P(96 kA) = 5% S_m=48.00 kA/μs	P(138 kA) = 2% S_m=58.61 kA/μs
100	2.32	🟩	🟩	🟩	🟩	🟩
200	4.65	🟩	🟩	🟩	🟩	🟩
300	6.97	🟩	🟩	🟩	🟩	⬜
400	9.30	🟩	🟩	🟩	🟩	🟥
500	11.62	🟩	🟩	🟩	🟩	🟥
600	13.95	🟩	🟩	🟩	⬜	🟥
700	16.27	🟩	🟩	🟩	🟥	🟥
800	18.60	🟩	🟩	🟩	🟥	🟥
900	20.92	🟩	🟩	⬜	🟥	🟥
1000	23.25	🟩	🟩	🟥	🟥	🟥
1200	27.90	🟩	🟩	🟥	🟥	🟥
1400	32.55	🟩	⬜	🟥	🟥	🟥
1600	37.20	🟩	🟥	🟥	🟥	🟥
1800	41.85	🟩	🟥	🟥	🟥	🟥
2000	46.49	🟩	🟥	🟥	🟥	🟥
2400	55.79	🟩	🟥	🟥	🟥	🟥
2800	65.09	⬜	🟥	🟥	🟥	🟥
3200	74.39	🟥	🟥	🟥	🟥	🟥
3600	83.69	🟥	🟥	🟥	🟥	🟥
4000	92.99	🟥	🟥	🟥	🟥	🟥

🟩	No back-flashover
⬜	Back-flashover depends on angle of the phase voltage
🟥	Back-flashover (does not depend on the angle of the phase voltage)

Table I confirms the correlation between the tower footing resistance and the occurrence of back-flashover.

Footing resistance is assumed as a parameter and the design of earth electrode was not specially considered. For lightning current amplitude (e.g. 31 kA) the back-flashover will certainly occur in the case of a lightning stroke to the tower with relatively high footing resistance (e.g. 75 Ω). If the lightning stroke to the tower has a current of relatively high amplitude (e.g. 96 kA) the back-flashover will certainly occur also in the case of lower tower footing resistance (e.g. 17 Ω).

Apart from the correlation considered, the back-flashover also depends on (maximal) steepness of the front of wave of the lightning current. If the steepness is higher, for a particular tower footing resistance, a back-flashover will also occur if the lightning current amplitude is smaller.

Fig. 9 depicts simulation results of back-flashover occurrences for different phase angles of the phase voltage. The following parameters are chosen for the simulation: lightning current amplitude 72 kA, maximal steepness S_m=40.98 kA/μs and tower footing resistance R=27.9 Ω. The back-flashover will certainly occur at least in one phase of the considered circuit of the double-circuit line for the chosen parameters. The phase angle of the voltage is changed in 7.5 degree steps. The angle of the voltage in the upper phase (A) is depicted on x-axis in Fig. 9, which shows that the back-flashovers in the middle phase (B) will occur for the largest range of the phase angles.

Table II shows simulation results for the case when one LSA is installed in the middle phase (B), which improves flashover characteristics of the HV line, which is obvious from comparison of Table I and Table II. It can be seen for two cases of the same lightning current (of 31 kA), that the tower footing resistance, for which the back-flashover will certainly occur, is now greater than 230 Ω.

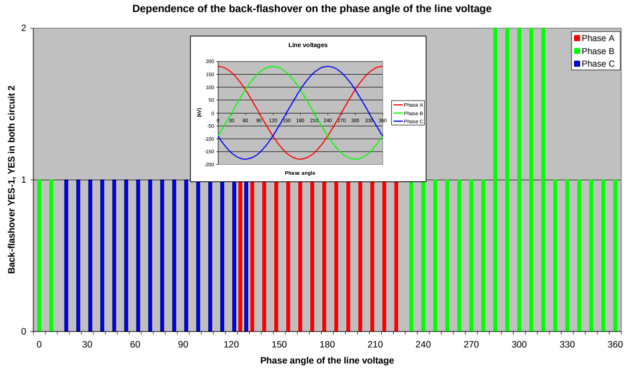

Fig. 9. Dependence of back-flashover on the phase angle of the voltages computed for I=72 kA, Sm=40.98 kA/μs, R=27.9 Ω

Installation of a LSA can be compared to other mitigation measures such as the decrease of the tower footing resistance. Because of that, it is important to determine which tower footing resistances to improve, before deciding whether to install LSAs. The cost of improving the tower footing resistance, if possible, should be compared with the cost of installing LSAs. The result of the comparison can help to make a decision regarding which footing resistances should be improved and on which towers LSAs should be installed. In some cases the installation of LSAs is the best solution for flashover prevention.

The following number of lightning strokes (per 100 km and per year) on a 220 kV line is adopted: N_L = 11.011. Fig. 10 and Fig. 11 are obtained by EMTP-RV LIPS simulations. LIPS has been developed in partnership by EDF, RTE and HYDRO-QUEBEC. It calculates the flashover rate of a line launching automatically EMTP-RV [28].

TABLE II
BACK-FLASHOVERS IN RELATION TO THE LIGHTNING CURRENT MAGNITUDE AND FOOTING RESISTANCE OF A TOWER, WITH SURGE ARRESTER IN THE MIDDLE PHASE (PHASE B)

ρ (Ωm)	R (Ω)	P(31 kA) = 50% S_m=25.78 kA/μs	P(52.8 kA) = 20% S_m=34.56 kA/μs	P(72 kA) = 10% S_m=40.98 kA/μs	P(96 kA) = 5% S_m=48.00 kA/μs	P(138 kA) = 2% S_m=58.61 kA/μs
400	9.30	🟩	🟩	🟩	🟩	🟩
500	11.62	🟩	🟩	🟩	🟩	🟩
600	13.95	🟩	🟩	🟩	🟩	⬜
700	16.27	🟩	🟩	🟩	🟩	⬜
800	18.60	🟩	🟩	🟩	🟩	⬜
900	20.92	🟩	🟩	🟩	🟩	⬜
1000	23.25	🟩	🟩	🟩	⬜	⬜
1200	27.90	🟩	🟩	🟩	⬜	🟥
1400	32.55	🟩	🟩	🟩	⬜	🟥
1600	37.20	🟩	🟩	⬜	⬜	🟥
1800	41.85	🟩	🟩	⬜	⬜	🟥
2000	46.49	🟩	🟩	⬜	🟥	🟥
2400	55.79	🟩	⬜	⬜	🟥	🟥
2800	65.09	🟩	⬜	⬜	🟥	🟥
3200	74.39	🟩	⬜	🟥	🟥	🟥
3600	83.69	🟩	⬜	🟥	🟥	🟥
4000	92.99	🟩	🟥	🟥	🟥	🟥
5000	116.24	🟩	🟥	🟥	🟥	🟥
6000	139.48	⬜	🟥	🟥	🟥	🟥
7000	162.73	⬜	🟥	🟥	🟥	🟥
8000	185.98	⬜	🟥	🟥	🟥	🟥
9000	209.23	⬜	🟥	🟥	🟥	🟥
10000	232.47	⬜	🟥	🟥	🟥	🟥

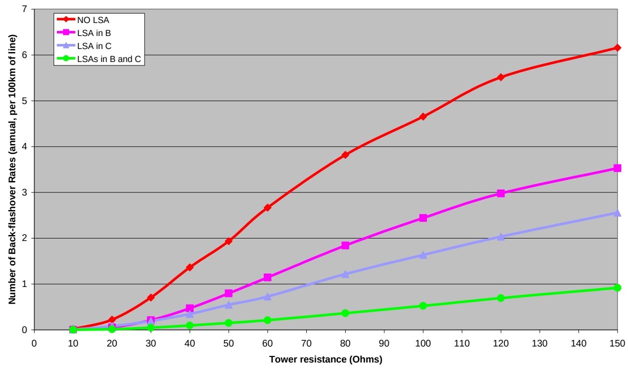

Fig. 10. Back-flashover rate of one circuit of the 220 kV line when it is not protected by LSAs, protected by LSA in middle phase (B), LSA in lower phase (C) and LSAs in lower and middle phases (B and C)

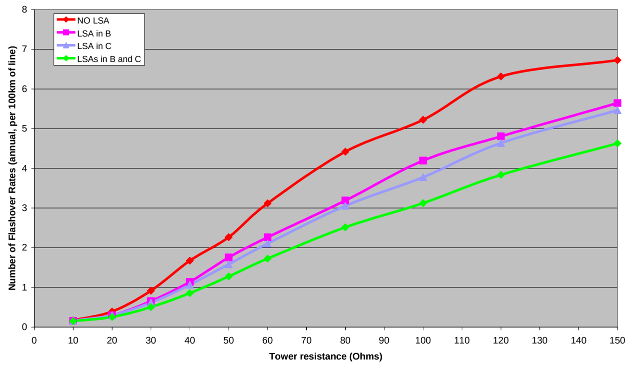

Fig. 11. Total flashover rate (back and shield failure) of 220 kV line when it is not protected by LSAs, protected by LSA in middle phase (B), LSA in lower phase (C) and LSAs in lower and middle phases (B and C)

Total flashover rate (back and shielding failure) of one circuit of the 220 kV line is slightly higher than rate shown on Fig. 10.

The following should be mentioned. If there is one tower with very high footing resistance (e.g. 250 Ω) then installation of three LSAs in one circuit will only prevent back-flashover in that circuit on that tower. Back-flashovers could occur on neighboring towers independently of the lower footing resistance of these towers. This is a consequence of the very high transient overvoltages on phase conductors, which travel to the neighboring towers and might lead to a flashover.

VI. Conclusions

For prevention of lightning flashovers on a line different mitigation measures could be applied and one of the most effective is the installation of LSAs. Double-circuit line outages could be significantly reduced by proper use of LSAs on one of the circuits. The final choice of the best solution depends on the number of LSAs, their location, their price and the practical constraints due to their installation. Calculations are conducted for the double-circuit 220 kV line using the software EMTP-RV and LIPS.

The locations of the LSA were assessed to optimize their effect on total outage rate; selected basically on magnitude of tower-footing resistance and lightning density on tower position received from LLS.

The following recommendations can be given for the 220 kV line case study conducted, for the purpose of optimization of the number of LSAs:

1. Improvement of the footing resistance on towers if economically justified.
2. No LSA (tower footing resistance < 21 Ω).
3. LSA in the lower phase (tower footing resistance >21Ω and <47Ω and the lightning density >10/km^2/year).
4. LSAs in the middle and lower phases (tower footing resistance > 47 Ω < 150 Ω and the lightning density >10/km^2/year).
5. Arresters installed in all 3 phases at selected towers with tower footing resistance > 150 Ω.

The installation of three LSAs in one circuit will only prevent back-flashover in that circuit on that tower and back-flashovers could occur on neighboring towers.

We should add that lightning is not the only cause of flashovers: pollution and wind in some regions can be the origin of significant number of faults.

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