Reduction of Flashovers on 220 kV Double-Circuits Line

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ABSTRACT

THE paper presents the results of a study for the reduction of the number of flashovers on a 220 kV double-circuit line. With known geometry of the tower and 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 evaluating the flashover rate. Models of the elements in the calculation are presented: source of lightning stroke, tower, conductors, insulator string, line surge arrester (LSA) and tower footing resistance. The case study for the 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 final choice of the best solution depends on the number of LSAs, their location and their price. Calculations are conducted using the software EMTP-RV and LIPS.

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. 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.

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 [1].

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. 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 [2].

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 to the rest of the power system. Several double-circuit outages provoked by lightning caused the interruption of power supply of the power plant and it was necessary to understand and prevent such outages. Calculation results for different line configurations, without and with LSAs, are compared.

II. 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 during a one year period. The average lighting stroke density for a given area is defined as the number of strokes per area unit during the one year 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. A 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 [3], can be approximated as following:

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

Where:

I - lightning current amplitude,

P - probability of occurrence of 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, [4] and [5].

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

$$R = a \cdot I^b \quad (2)$$

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]. 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. 1. Shielding wire and phase conductors of both circuits are modelled 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 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 finished with phase conductor strikes. There were a total of 37932 simulations conducted, of which 25635 finished with ground strikes, 11297 with 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,
- variance: 98.36 kA,
- standard deviation: 9.92 kA,
- maximal phase conductor strike current: 42.80 kA,
- critical current: 47.30 kA.

Critical current 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 finished with shielding failure – the distribution is shown in Fig. 2. 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 the current that can hit a phase conductor can be of high magnitude.

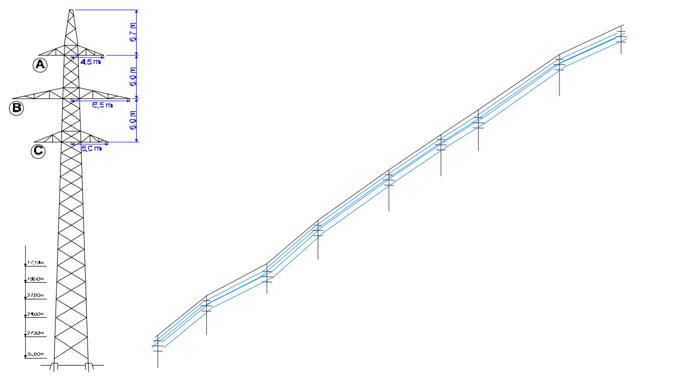

Fig. 1. 3D model of the part of the studied transmission line between towers 62 and 70.

Fig. 2 depicts the distribution of lightning currents striking phase conductors and Fig. 3 the distribution of currents hitting top of towers or shielding wire.

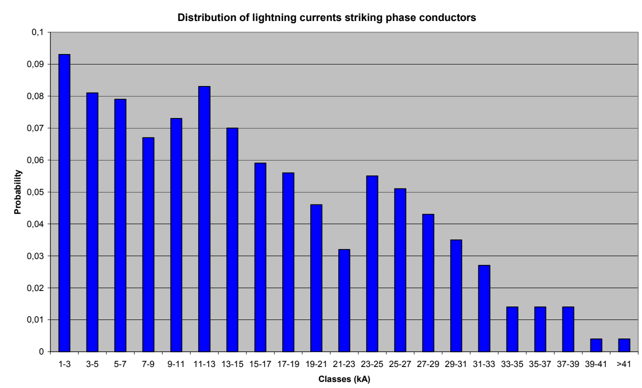

Fig. 2. Distribution of lightning currents striking phase conductors

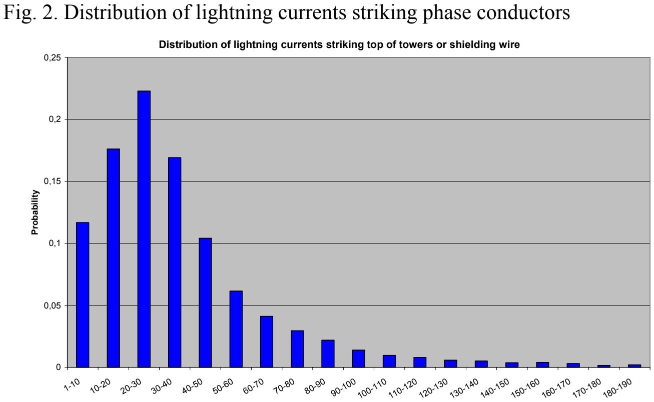

Fig. 3. Distribution of lightning currents striking top of towers or shielding wire

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

III. Modeling Procedure for Transient Simulations

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

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 LSA energy stresses, 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 [4] can approximate well the concave form of the lightning current front.

The transmission line, conductors and earth wire is 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 modelled in observing the flashovers of the insulators. To avoid reflection of travelling wave, 10 km of line is connected on both ends. Fig. 4 depicts the model used for simulation of lightning striking a double-circuit 220 kV line.

Tower surge impedances [6] 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. On this way it is possible to calculate transient voltages of tower arms.

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

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 behaviour 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 formula (4).

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

where:

$U(\tau)$ 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; 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).

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

$$R_i = \frac{R_o}{\sqrt{1 + \left(\frac{I}{I_g}\right)}} \quad (5)$$

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:

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

Where:

ρ - soil resistivity [Ωm];

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

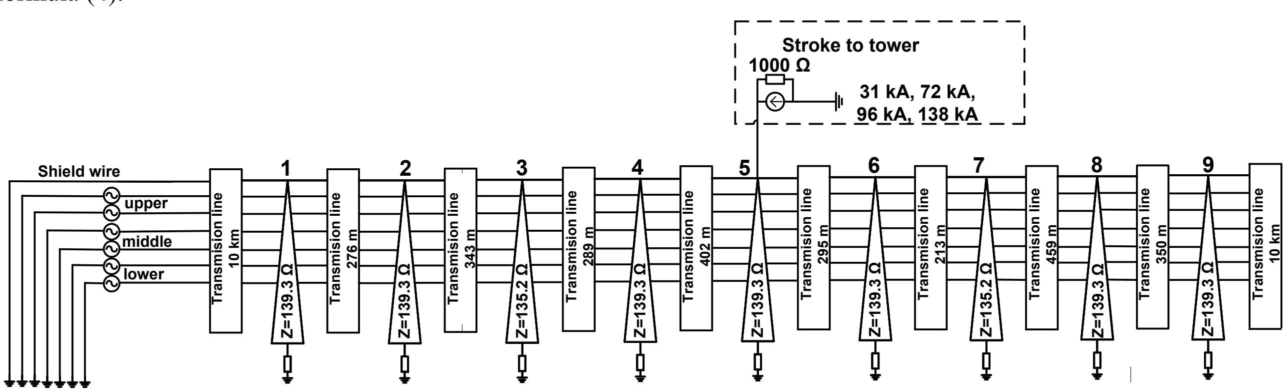

Fig. 4. Model of 220 kV double-circuit line

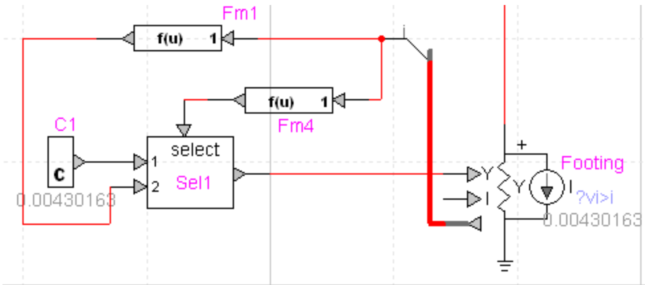

Fig. 5. EMTP-RV Model of footing resistance ionization, [8]

The model of gapless type LSA includes non-linear and dynamic behaviour of the arrester. The non-linear behavior is represented by the U-I characteristic depicted in Fig. 6.

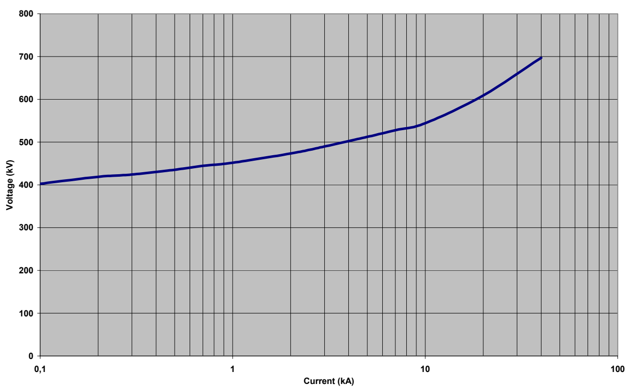

Fig. 6. U-I characteristic of surge arrester for the 220 kV line (U_r=210 kV)

IV. 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 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. Back-flashovers are considered because the intention was to maintain 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. The green colour indicates that back-flashover will not occur in any phase and for any combinations of phase angles of phase voltages. The grey colour 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, independent of the phase angle of the voltage, are marked with the red colour in Table I.

Table I confirmed the correlation between the tower footing resistance and the occurrence of back-flashover. For relatively small 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 relatively high current amplitude (e.g. 96 kA) 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 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 occur also if the lightning current amplitude is smaller.

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	green	green	green	green	green
200	4.65	green	green	green	green	green
300	6.97	green	green	green	green	grey
400	9.30	green	green	green	green	red
500	11.62	green	green	green	green	red
600	13.95	green	green	green	grey	red
700	16.27	green	green	green	red	red
800	18.60	green	green	green	red	red
900	20.92	green	green	grey	red	red
1000	23.25	green	green	red	red	red
1200	27.90	green	green	red	red	red
1400	32.55	green	grey	red	red	red
1600	37.20	green	red	red	red	red
1800	41.85	green	red	red	red	red
2000	46.49	green	red	red	red	red
2400	55.79	green	red	red	red	red
2800	65.09	grey	red	red	red	red
3200	74.39	red	red	red	red	red
3600	83.69	red	red	red	red	red
4000	92.99	red	red	red	red	red

(green) No back-flashover
(grey) Back-flashover depends on angle of the phase voltage
(red) Back-flashover (does not depend on the angle of the phase voltage)

Fig. 7 depicts simulation results of back-flashover occurrences for different phase angles of phase voltages. 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 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. 7, 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.

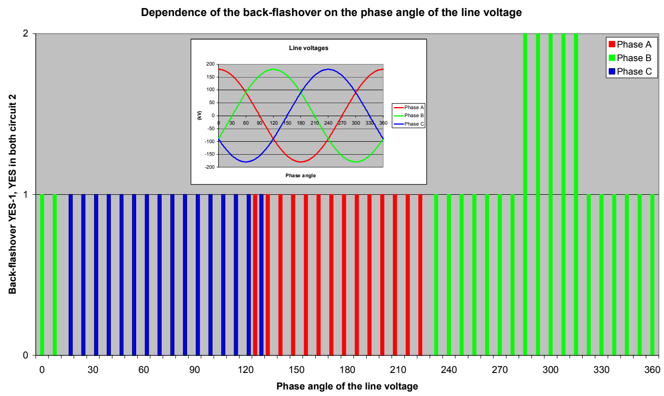

Fig 7. Dependence of back-flashover on the phase angle of the voltages computed for I=72 kA, Sm=40.98 kA/μs, R=27.9 Ω

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

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 evaluate which tower footing resistances could be improved, 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 reconstructed and on which towers LSAs should be installed.

The following number of lightning strokes (per 100 km and per year) on a 220 kV line is adopted: N_L = 11.011. Fig. 8 and Fig. 9 are obtained by EMTP-RV LIPS simulations. LIPS has been developed in partnership by EDF, RTE and HYDRO-QEBEC. It calculates the flashover rate of a line launching automatically EMTP-RV [9].

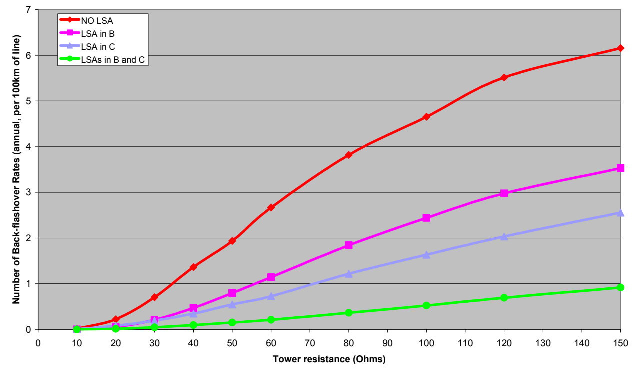

Fig. 8. Back-flashover rate of one circuit of the 220 kV line when it is not protected by LSAs, protected by LSA in middle phase (B), LSA in lower phase (C) and LSAs in lower and middle phases (B and C)

Total flashover rate (back and shielding failure) of one circuit of the 220 kV line is slightly higher then rate shown on Fig. 8.

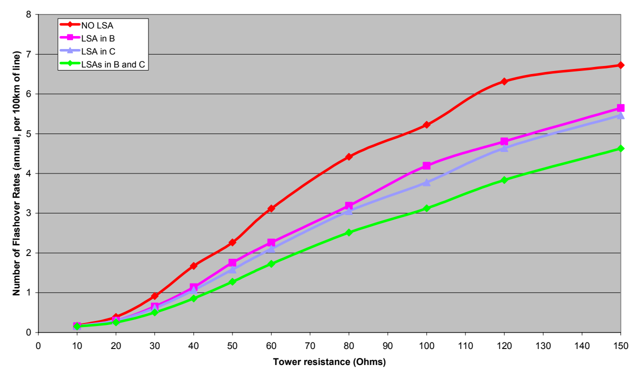

Fig. 9. Total flashover rate (back and shield failure) of 220 kV line when it is not protected by LSAs, protected by LSA in middle phase (B), LSA in lower phase (C) and LSAs in lower and middle phases (B and C)

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 neighbouring towers independently of lower footing resistance of these towers. This is a consequence of very high transient overvoltages on phase conductors, which travel to the neighbouring towers and flash over.

V. CONCLUSIONS

For prevention of flashovers on a line different mitigation measures could be applied and one of the most effective means 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 their installation. Calculations are conducted for the double-circuit 220 kV line using the software EMTP-RV and LIPS.

The locations of the arresters were assessed to optimize their effect on total outage rate; selected basically on magnitude of tower-footing resistance and experience from earlier lightning incidences.

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

1. Improvement of footing resistances on towers if economically justified.
2. No LSA (tower footing resistance < 21 Ω)
3. LSA in the lower phase (tower footing resistance > 21 Ω and < 47 Ω)
4. LSAs in the middle and lower phases (tower footing resistance > 47 Ω < 150 Ω)

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 neighbouring towers.

VI. References

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