# Assessment of the Lightning Flashover Rate of a Shielded Transmission Line Protected by Surge Arresters

Juan A. Martinez-Velasco, Ferley Castro-Aranda

**Abstract-- Surge arresters are installed to improve the lightning performance of overhead lines with a poor shielding or with very high tower footing impedances. The flashover rate of a shielded transmission line protected by surge arresters can be negligible when arresters are installed at all phases and all towers, but even if arresters are not installed at all phases, some improvement is achieved. However, arresters must be selected taking into account energy discharge stresses since failures can be caused when the energy discharged exceeds the maximum absorption capacity. This paper is aimed at analyzing the lightning performance improvement of a shielded transmission line that is achieved after installing surge arresters.**

**Keywords: Surge Arresters, Overvoltages, Modeling, Monte Carlo Method, Power System Lightning Effects.**

## I. INTRODUCTION

THE residual voltage developed across surge arresters installed to improve the performance of an overhead line is usually much lower than the insulation level of the line, irrespectively of the overvoltage cause, i.e. a shielding failure or a backflash. However, arresters have also to withstand the energy discharged by the lightning stroke. On the other hand, they do not have to be installed at all the line phases to obtain an improvement of the lightning performance. Therefore, an arrester study can be aimed at determining both the probability of arrester failure caused by the energy discharge stress and the improvement of the lightning flashover rate when arresters are not installed in all phases.

An accurate evaluation of the lightning performance of an overhead line must be based on a statistical approach due to the random nature of lightning [1], [2]. The simulation time of a Monte Carlo based method, when arresters are included in the transmission line, can be extremely long since the energy capability of arresters is also a random variable and simulation runs have to be expanded until the end of the stroke tail, which will be usually longer than 100 μs.

This paper presents the application of the ATP (Alternative Transients Program) to a study whose main goals are to determine the flashover rate improvement achieved by installing arresters, considering the possibility that they are not installed at all line phases. The study will be also aimed at estimating the energy absorption capability of arresters. The computation of flashover rates will be performed by using a Monte Carlo based method [2], while the energy absorption capability of surge arrester will be estimated by means of a sensitivity study.

Section II presents the transmission line configuration analyzed in this work. Section III details the lightning performance study of the test line before installing arresters. The study includes a summary of modeling guidelines and main aspects of the Monte Carlo procedure embedded by the authors in the ATP for flashover rate calculations [2]. Sections IV and V describe the studies dedicated to estimate respectively the required energy discharge capability of surge arresters and the lightning performance improvement of the test line after installing arresters.

## II. TEST LINE

Fig. 1 shows the tower design of the test transmission line, a 400 kV twin-circuit line, with only three phases asymmetrically arranged, two conductors per phase and one shield wire, see Table I.

If only a single-circuit has be provisionally installed, the lightning performance will be better when the three phases are placed at only one side of the tower because both the number of backflashovers and the number of shielding failures would be lower. This is very evident for the shielding failure flashover rate (SFFOR) because, when phases are at only one side, the upper phase will protect the other two phases, which does not occur with the configuration shown in Fig. 1. However, the maximum peak magnitude of strokes to phase conductors will be the same in both cases. This will be an important aspect, as shown in Section IV, for the selection of line surge arresters.

## III. LIGHTNING FLASHOVER RATE WITHOUT ARRESTERS

### A. Modeling Guidelines

The following paragraphs detail models used in this paper to represent the different parts of a transmission line [3] – [6].

1) The line (shield wires and phase conductors) is modeled by means of several spans at each side of the point of impact.

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TABLE I
LINE CONDUCTOR CHARACTERISTICS

| | Type | Diameter (mm) | Resistance (Ω/km) |
|---|---|---|---|
| Phase conductors | Cardinal | 30.35 | 0.0586 |
| Shield wire | 7N8 | 9.78 | 1.4625 |

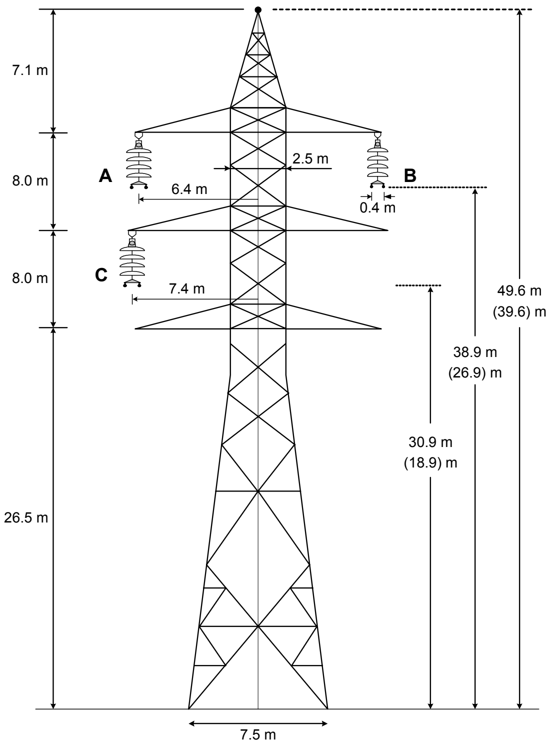



Fig. 1. 400 kV line configuration
(Values in brackets are midspan heights).

2) Each span is represented as a multi-phase untransposed constant- and distributed-parameter line section, whose parameters are calculated at 500 kHz [3].
3) The line termination at each side of the above model, needed to avoid reflections that could affect the simulated overvoltages around the point of impact, is represented by means of a long enough section, whose parameters are also calculated at 500 kHz.A tower is represented as an ideal single-conductor distributed-parameter line.
4) The footing impedance is represented as a non-linear resistance whose value is approximated by the following expression [3]

$$R_T = \frac{R_0}{\sqrt{1+I/I_g}} \qquad \left( I_g = \frac{E_0 \rho}{2\pi R_0^2} \right) \tag{1}$$

where $R_0$ is the footing resistance at low current and low frequency, $I$ is the stroke current through the resistance, and $I_g$ is the limiting current to initiate sufficient soil ionization, being $\rho$ the soil resistivity (Ω.m) and $E_0$ the soil ionization gradient (400 kV/m) [7].
5) The representation of insulator strings relies on the application of the leader progression model [1], [8], [9]. The leader propagation is deduced from the following equation

$$\frac{dl}{dt} = k_l V(t) \left[ \frac{V(t)}{g-l} - E_{l0} \right] \tag{2}$$

where $V(t)$ is the voltage across the gap, $g$ is the gap length, $l$ is the leader length, $E_{l0}$ is the critical leader inception gradient, and $k_l$ is a leader coefficient. For a more detailed description of this model see also [10].
6) A lightning stroke is represented as an ideal current source with a concave waveform. In this work return stroke currents are represented by means of the Heidler model [11]. A return stroke waveform is defined by the peak current magnitude, $I_{100}$, the rise time, $t_f$ (= 1.67 ($t_{90}$ – $t_{30}$)), and the tail time, $t_h$ (the time interval between the start of the wave and the 50% of peak current on tail).
A conversion procedure is performed to derive the parameters of the Heidler model from the stroke parameters mentioned above [12].
Lightning stroke parameters are assumed independently distributed, being their statistical behavior approximated by a log-normal distribution, with the following probability density function [13]

$$p(x) = \frac{1}{\sqrt{2\pi} x \sigma_{\ln x}} \exp\left[ -0.5 \left( \frac{\ln x - \ln x_m}{\sigma_{\ln x}} \right)^2 \right] \tag{3}$$

where $\sigma_{lnx}$ is the standard deviation of $lnx$, and $x_m$ is the median value of $x$.

### B. Monte Carlo Procedure

The main aspect of the Monte Carlo procedure embedded into the ATP can be summarized as follows [2]:

a) The calculation of random values includes the parameters of the lightning stroke (peak current, rise time, tail time, and location of the leader channel), phase conductor voltages, the footing resistance and the insulator strength.
b) The incidence model is based on the electrogeometric model as suggested in IEEE Std. 1243 [14].
c) Overvoltage calculations are performed once the point of impact has been determined.
d) If a flashover occurs in an insulator string, the run is stopped and the flashover rate updated.
e) The convergence of the Monte Carlo method is checked by comparing the probability density function of all random variables to their theoretical functions; the procedure is stopped when they match within the specified error.

### C. Transmission Line and Lightning Parameters

A model of the test line was created using ATP capabilities and following the guidelines summarized above.

- The line was represented by means of eight 390-m spans plus a 30-km section as line termination at each side of the point of impact.
- The surge impedance of towers was calculated according to the expression suggested by CIGRE [1]. A value of 195.1 Ω was estimated and used to represent all towers.

- Parameters used in the insulator equation were $k_l$ = 1.3E-6 $m^2/(V^2s)$ and $E_{l0}$ = 570 kV/m [1]. The striking distance of insulator strings was in all calculations 3.066 m.
- Only negative single stroke flashes were considered. They were represented by the Heidler model.

The following probability distributions were assumed:

- Stroke parameters were determined assuming a log-normal distribution. Table II shows the values selected for each parameter [13].

TABLE II
STATISTICAL PARAMETERS OF RETURN STROKES – BASE CASE

| Parameter | $x$ | $\sigma_{lnx}$ |
|---|---|---|
| $I_{100}$, kA | 34.0 | 0.740 |
| $t_f$, µs | 2.0 | 0.494 |
| $t_h$, µs | 77.5 | 0.577 |

- The phase conductor reference angle had a uniform distribution, between 0 and 360 degrees.
- Insulator string parameters were determined according to a Weibull distribution. The mean values were those mentioned above, while the standard deviation was 5% for all parameters.
- The footing resistance had a normal distribution with a mean value of 50 Ω and a standard deviation of 5 Ω. The value of the soil resistivity was 200 Ω.m.

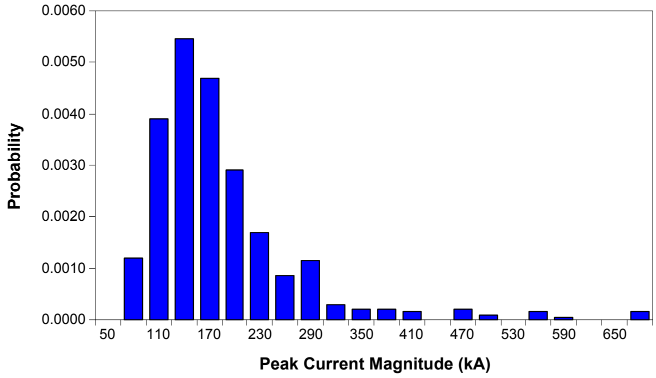
The stroke location, before the application of the electro-geometric model, was generated by assuming a vertical path and a uniform ground distribution of the leader.

No flashovers other than those across insulator strings, e.g. flashovers between conductors, were considered.

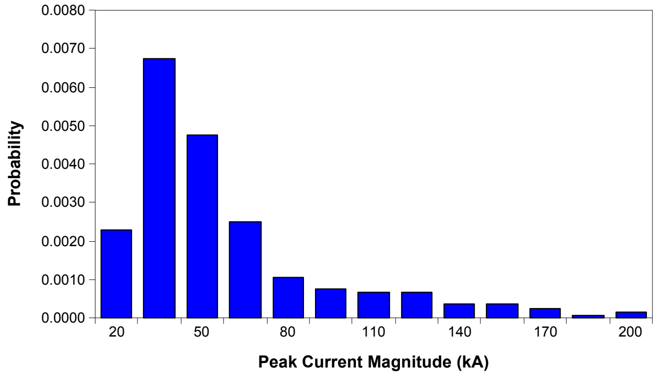
### D. Simulation Results

After 20000 runs, the flashover rates due to backflashovers and to shielding failures were respectively 2.330 and 2.060 per 100 km-year. The total flashover rate was, therefore, 4.390 per 100 km-year. These values were obtained with a ground flash density of $N_g$ = 1 fl/km$^2$-year. This flashover rate is unaccep-table for a transmission line since with an actual value of $N_g$ = 2 fl/km$^2$-year the total rate would be about 9 flashovers per 100 km-year.

Fig. 2 shows some simulation results that will help to understand the lightning performance of this line. One can observe that the peak current magnitude of the strokes that can cause flashover due to shielding failure can be as high as 180 kA, which is an abnormal value. To discriminate between an impact to ground, to a phase conductor or to a shield wire, the electrogeometric model as recommended in IEEE Std. 1243 has been used [14]. According to this model, return strokes with a peak current magnitude above 180 kA can reach a phase conductor of the test line. This is probably an unrealistic result, although shielding failures with peak current magnitudes above 100 kA should be expected, which proves that the line has a poor shielding. This can justify the high shielding failure flashover rate (SFFOR).




a) Strokes to shield wires that caused flashover




b) Strokes to phase conductors that caused flashover

Fig. 2. Distribution of stroke currents.

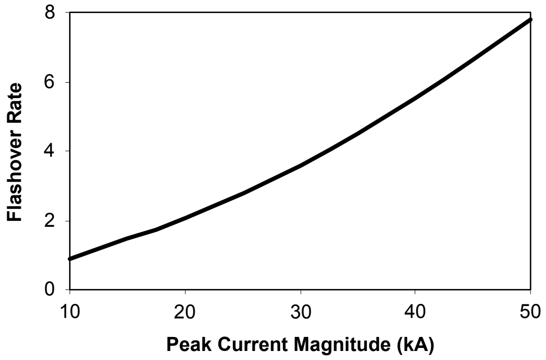
A high footing resistance (above 20 Ω) and a short strike distance are two aspects that can affect the backflashover rate. In addition, Fig. 2a, shows that a non-negligible percentage of backflashovers were caused by strokes with a peak current magnitude above 300 kA; these high values result from the theoretical statistical distribution of stroke parameters, but they will not frequently occur in reality. All these factors can justify the high backflshover rate.

### E. Sensitivity Analysis

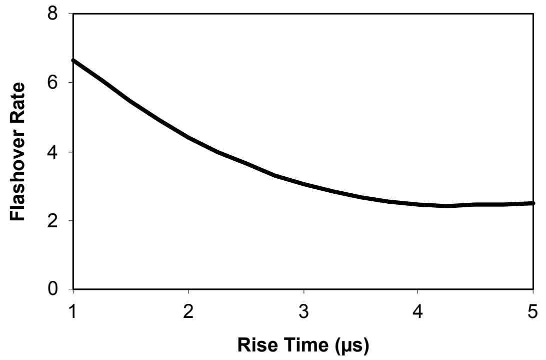
A sensitivity analysis was performed to find out the relationship between the flashover rate of the test line and some critical parameters, namely the median value of the peak current magnitude and the rise time of lightning strokes, as well as the mean value of the footing resistance at low current and low frequency.

Fig. 3 shows the results. As for the previous calculations, the flashover rates are given per 100 km-year and they were obtained with $N_g$ = 1 fl/km$^2$-year.

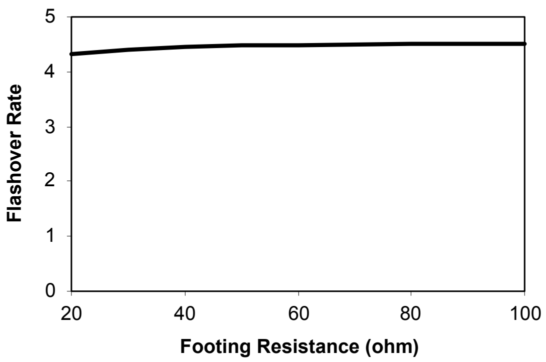
These results show an expected trend. The flashover rate increases when the median value of the peak current magnitude increases; however, the rate decreases when the median value of the rise time increases. One can note that, even with $N_g$ = 1 fl/km$^2$-year, the flashover rate is too high when the peak current magnitude is large and the wave front very steep.




a) Flashover rate vs. peak current magnitude
($t_f = 2$ µs, $t_{fh} = 77.5$ µs, $R_0 = 50$ Ω, ρ = 200 Ω.m)




b) Flashover rate vs. rise time
($I_{100} = 34$ kA, $t_h = 77.5$ µs, $R_0 = 50$ Ω, ρ = 200 Ω.m)




c) Flashover rate vs. footing resistance
($I_{100} = 34$ kA, $t_f = 2$ µs, $t_h = 77.5$ µs, ρ = 200 Ω.m)

Fig. 3. Sensitivity analysis ($N_g = 1$ fl/km$^2$-year).

As for the footing resistance value, the variation of the flashover rate is not very significant within the range of values analyzed in this paper. This can be due to the effect of soil ionization and to the high percentage of flashovers that are caused by strokes that reach a phase conductor, for which the influence of the footing impedance is negligible.

## IV. Arrester Energy Analysis

### A. Modeling Guidelines

Some modeling guidelines used in the calculation of the flashover rate are no longer valid when the main goal is to estimate the energy discharged by arresters. The most important differences can be summarized as follows [15], [16]:

- Spans must be represented as multi-phase untransposed frequency-dependent distributed-parameter line sections, since the calculations with a constant parameter model can produce wrong results during the stroke tail, when the steepness of the current is variable and lower than during the front of the wave.
- No less than 7 spans at both sides of the point of impact have to be included in the model for arrester energy evaluation.
- The representation of the tower footing impedance is a critical aspect when the stroke hits a tower, but the influence of the model selected for this resistance is almost negligible when the stroke hits a phase conductor.
- The effect of the arrester lead is negligible when strokes hit either a tower or a phase conductor.
- The tail time of the return stroke current has a strong influence, being the effect of the rise time very small, or even negligible for low peak current values.

### B. Arrester Model and Parameters

The model chosen in this work for representing surge arresters is that recommended by IEEE [17]. The following values are used to obtain this model:

- voltage for a 10 kA, 8/20 µs current, $V_{10} = 1007$ kV;
- switching surge discharge voltage for 1 kA, 30/60 µs current, $V_{ss} = 735$ kV;
- height of the arrester, $d = 3.72$ meters;
- number of parallel columns of MO disks, $n = 1$.

On the other hand, the rated voltage selected for the test arrester is 378 kV.

### C. Sensitivity Analysis

A line model with the guidelines discussed above was created to estimate the configuration (i.e., line phases at which arresters are installed) with which the energy discharged by arresters could reach the maximum value when the stroke hits either a tower or a phase conductor. Table III shows the results, which were obtained with a footing resistance model for which $R_0 = 50$ Ω and $\rho = 200$ Ω.m. The calculations were made with arresters installed in all towers and assuming that the reference phase angle (phase A angle) was 0º.

As indicated at the bottom of the table, the peak current magnitude used to obtain the maximum discharged energy when the stroke hits a tower is different from that assumed when the stroke hits a phase conductor. The placement of a single arrester at phase C (see Fig. 1) was not studied since only very low peak current magnitude vertical-path strokes will reach that phase.

From the results shown in the table one can deduce that differences between the maximum energy stress deduced with each configuration are very small when the stroke hits a phase conductor; that is, when the stroke hits a phase conductor, the maximum energy discharged by the arrester installed at the struck phase is very similar in all cases.

Differences between the scenarios analyzed in this study are more important when the stroke hits a tower, although energy values are much smaller. This is due to the fact that with a 150 kA stroke, a flashover will always occur unless arresters were installed at all phases.

As expected, the maximum energy stress in arresters corresponds to a return stroke that impacts a phase conductor.

TABLE III
MAXIMUM ENERGY DISCHARGED BY SURGE ARRESTERS

| Arresters per tower | Stroke to a tower (1) | Stroke to a phase conductor (2) |
|---|---|---|
| A – B – C | 8.58 kJ | 600.1 kJ |
| A – B | 11.19 kJ | 600.0 kJ |
| B – C | 12.30 kJ | 581.9 kJ |
| C – A | 11.27 kJ | 600.1 kJ |
| A | 15.45 kJ | 600.0 kJ |
| B | 16.07 kJ | 581.9 kJ |

Notes: (1) Waveform of the stroke to a tower = 150 kA, 2/50 μs
(2) Waveform of the stroke to a conductor = 50 kA, 2/50 μs

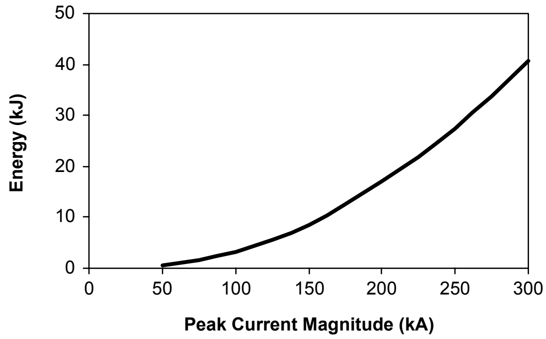
A conclusion from the results shown in the table is that the estimation of the maximum energy stress can be performed by assuming that arresters are installed at all the phases.

Plots of Fig. 4 show the results from a new sensitivity study aimed at estimating the maximum energy discharged by arresters considering a different range of peak current values for strokes to a tower or to a phase conductor.

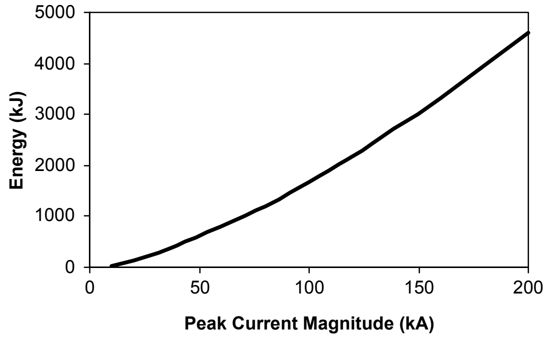
Although the peak current values of return strokes that hit a tower can reach values larger than 300 kA, one can conclude from the first plot that the impact of a stroke to a tower will not cause arrester failure, since even selecting the lowest single impulse energy absorption capability, arresters will be able to withstand such energy stresses.

The conclusion when the stroke hits a phase conductor is different. The maximum energy discharged by arresters progressively increases and reaches very high values. With a 180 kA stroke, the energy discharged by the arrester installed at the struck phase is about 4000 kJ. To avoid arrester failure, the single impulse energy absorption capability of arresters should be more than 10 kJ/kV. Although some results presented in this study (namely the flashover rate due to shielding failures) are debatable, strokes with a peak current magnitude above 120 kA will reach phase conductors if electrogeometric models different from that applied in this work were considered. In any case, it is also evident that arresters with a large energy absorption capability have to be selected.

The calculations were made with a stroke waveform of 2/50 μs. The influence of the rise time on the energy discharged by the arrester is negligible, but this energy will increase with tail time. That is, a stroke with a tail time of 100 μs will be even more dangerous.




a) Strokes to a tower




b) Strokes to a phase conductor

Fig. 4. Energy discharged by surge arresters. (Stroke waveform = 2/50 μs; Footing resistance: $R_0$ = 50 Ω, $\rho$ = 200 Ω.m).

The footing resistance parameters could be different from those used to obtain Fig. 4b, but their influence, when the stroke hits a phase conductor, is unimportant. That is, energy values with different footing resistances will be very similar to those depicted in Fig. 4b.

## V. LIGHTNING FLASHOVER RATE WITH ARRESTERS

The goal of the new study is to estimate the improvement of the flashover rate that can be achieved by installing surge arresters at all towers of the test line, but not at all phases.

The following conclusions were derived from the results presented and discussed in the previous sections:

- The line has a poor lightning performance, which is mainly due to an abnormal shielding failure rate, although the backflashover rate is also very high.
- An arrester failure can be caused by a stroke to a phase conductor, unless arresters with a large energy absorption capability were installed.

The flashover rate of the test line with the different combinations of arresters analyzed in the previous section (see Table III) was estimated. The new simulations were performed without measuring the energy discharged by arresters; that is, it was assumed that arresters with a large enough energy absorption capability were installed, so the line model, as well as return stroke parameters, were those detailed in Section II. Table IV shows a summary of the new results.

The following conclusions are derived from these results:

- As expected, when arresters are installed at all phases, the total flashover rate is reduced to zero.

- Shielding failures are significantly reduced when only two arresters are installed at the upper phases. This is due to the protection provided by phase A, which will avoid that most return strokes reach the bottom phase.
- Consequently, when arresters are installed at two phases, the best performance is achieved when they are installed at the upper phases.
- The difference between the rates obtained when only one arrester is installed is not too large, and it is mainly due to the different backflashover rates that are obtained with each scenario.

TABLE IV
FLASHOVER RATE WITH ARRESTERS (PER 100 KM-YEAR)

| Arrester Protection | BFOR | SFFOR | Total flashover rate |
|---|---|---|---|
| A – B – C | 0 | 0 | 0 |
| A – B | 0.390 | 0.005 | 0.395 |
| B – C | 0.725 | 0.990 | 1.715 |
| C – A | 0.965 | 1.090 | 2.055 |
| A | 1.335 | 1.095 | 2.430 |
| B | 1.395 | 1.005 | 2.400 |

## VI. CONCLUSIONS

This paper has presented the results of a study whose main goal was to analyze the lightning performance improvement of a 400 kV line with a very poor shielding.

The study has shown that a different degree of improvement can be achieved by installing arresters at all or only some of the line phases. The improvement can be very significant when arresters are installed at two phases, but even with the installation of a single arrester per tower at the upper phase, an important reduction of the total flashover rate can be achieved. In all cases, arresters with a high energy absorption capability are required.

There are several aspects of this work for which a deeper study is advisable. Some of them are justified in the following paragraphs:

- All simulations were based on the same tower model [1], but the energy discharged by arresters can be very dependent on the tower model, see [15] and [18].
- Since a significant percentage of lightning flashes have more than one stroke, an energy absorption capability even higher than that obtained in this work could be required.
- It is, however, the very poor shielding of the line analyzed in this paper the most important aspect. A more accurate assessment of the SFFOR could be advisable for an adequate selection of arresters. Since there is no agreement on the most accurate incidence model, a sensitivity study that could compare the different SFFOR obtained with other incidence models proposed could be useful to fix more accurately the performance of the shielding design analyzed in this work.

A rigorous selection of the arrester energy capability could be based on an arrester failure rate, taking into account that even this parameter has a random nature, and on a statistical study.

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## VIII. BIOGRAPHIES


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