# LINE SURGE ARRESTER ENERGY DUTY CONSIDERATIONS ON THE COMPACT UNSHIELDED TRANSMISSION LINES

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**Abstract**: This Paper presents results of the study performed in order to reduce energy duties of the Line Surge Arresters installed on the double circuit, vertical configuration unshielded line. Arrester energy duty reduction is obtained by the installation of the lightning rods on the tower tops. According to the Electro geometric model, lightning rods are collecting 'high energy' lightning strokes, which help in the arrester energy duty reduction. Different lightning rod heights and tower footing resistances are considered through the study. Surge arrester currents and energy duties are presented. Line surge current shapes for the different lightning stroke locations are also given.

## 1 INTRODUCTION

In the selection of Line Surge Arrester (LSA) design parameters it is very important to know electrical and mechanical stresses to which LSA will be exposed in the real field. LSA may fail in the service if not correctly selected. Expected arrester energy duty is of extreme importance for the selection of the ZnO block size (arrester class).

Arrester energy duty, which is mainly related to the LSA current shape, may be determined by the software simulation tools [1] or by the field measurement.

It is well known that LSA installed on the unshielded lines are more stressed than LSA installed on the shielded lines [2].

Shield wire on the shielded line collects high energy lightning strokes, diverts current through towers and tower footing resistances and changes shape of the lightning current through LSA.

In the case of the unshielded line, lightning strokes are hitting directly phase conductors on which LSA are installed. Shape of the LSA lightning current is similar to the shape of the original lightning stroke. These are the main reasons for the very high-energy duties of the LSA installed on the unshielded lines.

In this paper we examine the influence of the short lightning rods installed on the tower tops in order to collect high-energy lightning strokes in the case of the unshielded lines. According to the Electro Geometrical Modelling, these rods should collect lightning strokes having higher stroke amplitudes. In this case only strokes with moderate amplitudes could hit directly phase conductors. LSA can easily handle lightning strokes having moderate current peaks.

In order to verify results of the computer simulations a pilot-monitoring project is proposed. Sophisticated monitoring equipment would be installed to monitor LSA and lightning rods current shapes in real time.

## 2 COMPACT LINES

Thanks to the development of the composite line post insulators, compact line design becomes a very realistic alternative to the standard line designs. Efficient use of the right-of-ways with minimal environmental impact has become one of the primary objectives when planning new line designs. When designing compact lines a very careful analysis of its electrical and mechanical parameters is necessary because of the reduction of design margins.

The use of line surge arresters in the compact line design insulation coordination becomes a very important task. The quality of the service of the compact lines can be substantially improved by the use of these devices.

LSA installed on the top conductors of the double circuit, vertical configuration compact unshielded line can substantially improve line lightning performance [3]. For this type of the arrester application it is important to take into account that the majority of the lightning stroke terminate on top conductors. Direct strokes to the top conductors (on which surge arresters are installed) may deliver substantial energy through the arresters. A careful computer simulation is needed for the determination of LSA energy duty.

The main idea of the study presented in this paper is to use short lightning rods installed on the top of the double circuit vertical configuration unshielded line. Lightning rods installed on the tower tops are collecting high current (high energy) lightning strokes, reducing energy duty of the installed LSA. In this case LSA are less stressed (by the strokes hitting phase conductors) which allow selection of LSA having lower energy capability.

Influence of the lightning rod heights on the LSA lightning stroke currents and energies distributions is studied. Line lightning performance of the line without LSA, but with lightning rods installed is also studied.

Installation of the lightning rods on the tower tops change distribution of the lightning stroke to line. Added lightning rods increase number of strokes collected by the line. Strokes termination on the rods may produce backflashovers, even in the case when LSA are installed on the top conductors. Number of the backflashovers depends on the tower footing resistance.

# 3 STUDIED LINE

## 3.1 Study data

Tower top of the studied 138 kV double circuit unshielded line is presented in Fig. 1 [3]. LSA are installed on the top conductors only. LSA having rated voltage (duty cycle voltage) of 120 kV are used.

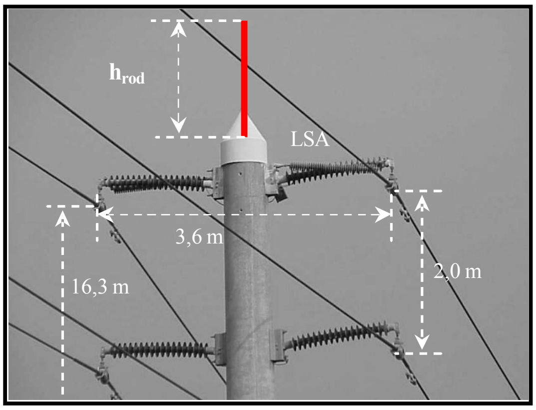


Figure 1 - 138 kV double circuit-unshielded line
Top conductor LSA

Sigma slp software [1] is used in all simulations. For each statistical case a total number of 2000 simulations are performed. In the 3D Electro geometric (EGM) modelling it was considered that striking distance to the lightning rods is 5 % higher than to the phase conductors.

Studied line has 106 m spans and tower surge impedance is 182 Ω. Ground flash density is 8,09 strokes/km$^2$/y.

Line post insulators critical flashover voltage is 770 kV. In the Monte Carlo simulation it was assumed that the line insulation characteristic is also random (normal distribution, $\sigma$ =3 %).

## 3.2 Results of the EGM modelling

Results of the 3D EGM modelling for different lightning rods heights are given in Table 1.

Table 1 - Results of the EGM modelling
Different lightning rod heights

| $h_{rod}$(m) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| $W_E$(m) | 103,9 | 112,1 | 113,0 | 115,1 |
| $N_L$(*) | 29,1 | 31,4 | 31,6 | 32,2 |

Following data is presented in Table 1:
$h_{rod}$ - Lightning rod height (m)
$W_E$ - Line shadow width (m)
$N_L$- Number of strokes collected by the line (strokes/100km/year)

Case $h_{rod}$ = 0 corresponds to the line without lightning rods. Added lightning rods having the heights of 1 m, 2 m and 3 m are considered.

As expected, number of the strokes collected by the line is increasing with the increase of the lightning rods heights.

# 4 LINE LIGHTNING PERFORMANCE

## 4.1 Line without LSA

We present here simulation results for the line without LSA. Influence of the tower footing resistance and lightning rods heights is studied. Tower footing resistance variation from 5 Ω to 20 Ω is analysed. A soil ionisation non-linear tower footing resistance model is used. The ratio between soil resistivity and tower low current footing resistance is taken to be 30.

Line backflashover rate is presented in Table 2. These flashovers happen when lightning stroke hits lightning rod. For the tower footing resistance of 5 Ω backflashovers are completely eliminated, doesn't matter what is lightning rod height. For the higher footing resistance (15 Ω and 20 Ω) backflashover rate is increasing with the footing resistance increase.

In Table 3, line shielding failure flashover rate is presented. As expected shielding failure flashover rate doesn't depend on the tower footing resistance. By the introduction of lightning rod, shielding failure rate is decreased (more that three times compared to the case without lightning rods).

Influence of the tower footing resistance and the lightning rods heights on the line total flashover rate is given in Table 4. Line total flashover rate is a simple sum of the backflashover and shielding failure flashover rates given in Table 2 and 3 respectively.

Line double circuit flashover rate is presented in Table 5.

Table 2 - Line Backflashover rate
Without LSA
[Flashovers/100 km/year]

| $h_{rod}$(m) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| R = 5 Ω | 0 | 0 | 0 | 0 |
| R = 10 Ω | 0 | 0,89 | 0,85 | 1,00 |
| R = 15 Ω | 0 | 4,22 | 4,15 | 4,70 |
| R = 20 Ω | 0 | 8,29 | 8,57 | 9,51 |

Table 3 - Line Shielding Failure Flashover rate
Without LSA
[Flashovers/100 km/year]

| $h_{rod}$(m) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| R = 5 Ω | 29,65 | 8,82 | 7,62 | 7,16 |
| R = 10 Ω | 29,65 | 8,82 | 7,62 | 7,16 |
| R = 15 Ω | 29,65 | 8,82 | 7,62 | 7,16 |
| R = 20 Ω | 29,65 | 8,82 | 7,62 | 7,16 |

Table 4 - Line Total Flashover rate
Without LSA
[Flashovers/100 km/year]

| $h_{rod}$(m) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| R = 5 Ω | 29,65 | 8,82 | 7,62 | 7,16 |
| R = 10 Ω | 29,65 | 9,71 | 8,47 | 8,16 |
| R = 15 Ω | 29,65 | 13,04 | 11,77 | 11,86 |
| R = 20 Ω | 29,65 | 17,11 | 16,19 | 16,68 |

Table 5 - Line Double Circuit Flashover rate
Without LSA
[Flashovers/100 km/year]

| $h_{rod}$(m) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| R = 5 Ω | 0 | 0 | 0 | 0 |
| R = 10 Ω | 0 | 0 | 0,01 | 0 |
| R = 15 Ω | 0,02 | 0,07 | 0,16 | 0,09 |
| R = 20 Ω | 0,1 | 0,62 | 0,49 | 0,64 |

### 4.2 LSA installed on the top conductors

IEC Class I polymer housed LSA, having rated voltage of 120 kV are installed on the top phase conductors. Line total and double circuit flashover rates are given in Tables 6 and 7 respectively. For the line without additional lightning rods, both flashover rates are zero.

When lightning rods are installed line total flashover rate is slightly increased for tower footing resistance equal or higher than 10 Ω. Lightning rods are collecting stroke current with the higher peaks, producing backflashovers for the higher footing resistance.

Table 6 - Line Total Flashover rate
LSA top conductors
[Flashovers/100 km/year]

| $h_{rod}$(m) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| R = 5 Ω | 0 | 0 | 0 | 0 |
| R = 10 Ω | 0 | 0,078 | 0,111 | 0,079 |
| R = 15 Ω | 0 | 0,722 | 0,760 | 0,726 |
| R = 20 Ω | 0 | 1,827 | 1,868 | 1,748 |

Table 7 - Line Double Circuit Flashover rate
LSA top conductors
[Flashovers/100 km/year]

| $h_{rod}$(m) | 0 | 1 | 2 | 3 |
|---|---|---|---|---|
| R = 5 Ω | 0 | 0 | 0 | 0 |
| R = 10 Ω | 0 | 0 | 0 | 0 |
| R = 15 Ω | 0 | 0 | 0 | 0 |
| R = 20 Ω | 0 | 0,016 | 0 | 0,080 |

## 5 STATISTICAL DISTRIBUTION OF THE LSA CURRENTS

During statistical studies LSA currents are monitored for the different tower footing resistances and lightning rods heights. Cumulative distributions of the LSA are determined for each studied case. Selected values from the LSA currents cumulative distributions are presented in Tables 8 to 11 (2 %, 5%, 10% and 20 % probabilities).

According to the presented results we can conclude that the added lightning rods substantially decrease LSA current peaks. LSA current peaks are almost three times reduced, even for the 1 m long (short) rod.

Table 8 - **2 %** values of LSA currents

| $h_{rod}$(m) | R = 5 Ω | R = 10 Ω | R = 15Ω | R = 20 Ω |
|---|---|---|---|---|
| 0 | 47,19 | 44,06 | 42,78 | 40,63 |
| 1 | 16,71 | 15,58 | 16,50 | 17,37 |
| 2 | 15,89 | 15,55 | 15,62 | 16,76 |
| 3 | 14,34 | 14,25 | 14,62 | 15,27 |

Table 9 - **5 %** values of LSA currents

| $h_{rod}$(m) | R = 5 Ω | R = 10 Ω | R = 15Ω | R = 20 Ω |
|---|---|---|---|---|
| 0 | 32,83 | 30,92 | 30,32 | 29,12 |
| 1 | 12,02 | 11,60 | 12,49 | 13,70 |
| 2 | 11,66 | 11,85 | 12,42 | 12,95 |
| 3 | 10,15 | 9,83 | 11,52 | 12,51 |

Table 10 - **10 %** values of LSA currents

| $h_{rod}$(m) | R = 5 Ω | R = 10 Ω | R = 15Ω | R = 20 Ω |
|---|---|---|---|---|
| 0 | 23,52 | 23,46 | 22,40 | 22,10 |
| 1 | 6,12 | 7,82 | 8,85 | 10,1 |
| 2 | 6,32 | 7,45 | 8,92 | 9,82 |
| 3 | 4,47 | 4,89 | 7,73 | 8,86 |

Table 11 - **20 %** values of LSA currents

| $h_{rod}$(m) | R = 5 Ω | R = 10 Ω | R = 15Ω | R = 20 Ω |
|---|---|---|---|---|
| 0 | 15,76 | 15,42 | 15,02 | 14,67 |
| 1 | 1,06 | 2,42 | 4,26 | 6,29 |
| 2 | 1,04 | 2,17 | 4,26 | 6,03 |
| 3 | 0,87 | 1,77 | 3,49 | 4,96 |

## 6 LSA ENERGY DUTIES

Taking into account that a full statistical study for the arrester energy duty determination is time consuming, it was decided to determine LSA energy duty for the selected lightning stroke peaks (30 kA, 50 kA, 75 kA and 100 kA). Lightning stroke having peak of 30 kA has a probability of around 50 %, while probability of 100 kA strokes is around 2 %.

Lightning rod being 1 m long is taken in all simulations. Tower footing resistance from 5 Ω to 20 Ω is considered. Three different stroke locations are studied:

Rod (1 m): Stroke to the lightning rod
PHC_TOW: Stroke to Phase Conductor - Tower
PHC_MID: Stroke to Phase Conductor - Midspan

According to the presented results we can see a substantial reduction of the arrester energy duty, especially for the lower values of the tower footing resistance. For example, when tower footing resistance is 5 Ω, arrester energy duty is reduced for more than forty times, even for 100 kA lightning stroke peak (2 % probability). This reduction is even higher for the lightning strokes having lower peak.

For the higher footing resistance values (15 Ω and higher), the corresponding reduction is lower but still of interest.

With the LSA energy duty reduction by the installation of the short lightning rods on the tower tops, we can use LSA of lower IEC Class (for example distribution class LSA instead of IEC Class II or III). Distribution class LSA are lighter, easier to install and much cheaper.

Table 12 - LSA energies (kJ)
R= 5 Ω, $h_{rod}$ = 1 m

| | Current (kA) | | | |
|---|---|---|---|---|
| Stroke to | 30 | 50 | 75 | 100 |
| Rod (1m) | 0,3 | 2,9 | 7,9 | 14,7 |
| PHC_TOW | 120,8 | 241,6 | 419,7 | 627,7 |
| PHC_MID | 94,5 | 185,8 | 313,2 | 457,4 |

Table 13 - LSA energies (kJ)
R= 10 Ω, $h_{rod}$ = 1 m

| | Current (kA) | | | |
|---|---|---|---|---|
| Stroke to | 30 | 50 | 75 | 100 |
| Rod (1 m) | 4,5 | 13,3 | 40,4 | 128,9 |
| PHC_TOW | 104,4 | 202,3 | 343,6 | 505,5 |
| PHC_MID | 85,9 | 164,0 | 271,5 | 391,2 |

Table 14 - LSA energies (kJ)
R= 15 Ω, $h_{rod}$ = 1 m

| | Current (kA) | | | |
|---|---|---|---|---|
| Stroke to | 30 | 50 | 75 | 100 |
| Rod (1 m) | 10,6 | 44,7 | 162,4 | 299,6(*) |
| PHC_TOW | 94,6 | 180,5 | 303,4 | 443,5 |
| PHC_MID | 80,5 | 151 | 247,7 | 354,8 |

(*) - Backflashover

Table 15 - LSA energies (kJ)
R= 20 Ω, $h_{rod}$ = 1 m

| | Current (kA) | | | |
|---|---|---|---|---|
| Stroke to | 30 | 50 | 75 | 100 |
| Rod (1 m) | 18,8 | 98,6 | 269,0 | 136,8(*) |
| PHC_TOW | 88,1 | 166,7 | 278,9 | 407,6 |
| PHC_MID | 76,7 | 142,5 | 232,9 | 332,6 |

(*) - Backflashover

Taking into account that LSA energy duty is directly related to the LSA current shape we did several 'single stroke' simulations.

First simulation case corresponds to the lightning stroke having 75 kA hitting lightning rod top, phase conductor at the tower position and phase conductor at midspan. Lightning rod height is 1 m and tower footing resistance of 10 Ω is used in this simulations. LSA current shapes are given in Fig. 2.

Presented LSA current shapes clearly indicate why stroke hitting lightning rod top produce lowest LSA energy duty.

Second single stroke simulation case corresponds to the lightning stroke having 75 kA peak, hitting 1 meter long (short) rod, but this time with the different tower footing resistance (from 5 Ω to 20 Ω) - Fig.3.

As expected lower tower footing resistance better diverts lightning stroke current to the ground, thus reducing LSA current and energy.

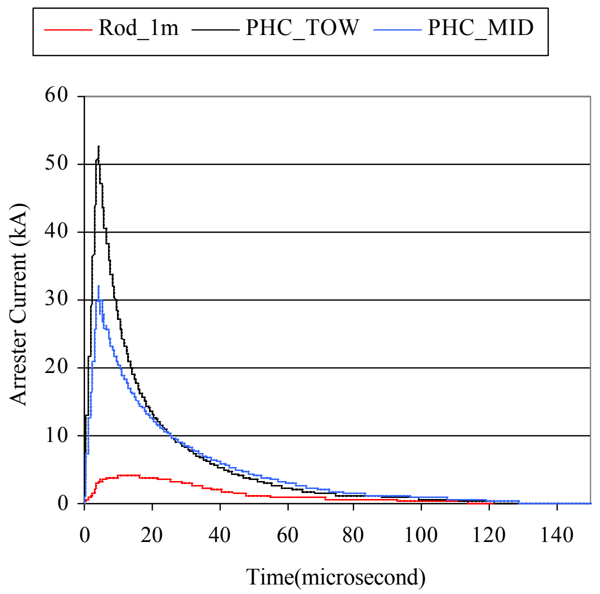


Figure 2 - LSA current shapes for the different lightning stroke locations (75 kA peak, R = 10 Ω)

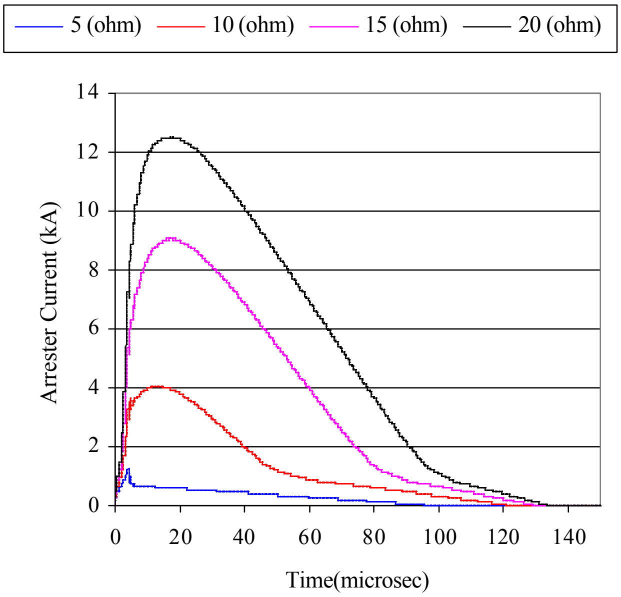


Figure 3 - LSA current shapes for the different tower footing resistance (75 kA peak hitting top of the 1m long rod )

## 7 PILOT PROJECT

In order to verify results obtained in this study it is planned to develop the corresponding pilot project. The main idea is to install the real time monitoring system, described in [2] for the LSA and lightning rods current shapes monitoring.

Top conductors LSA and 1 m long lightning rod current shapes would be monitored in real time by the use of impulse current transformers. A four channel high speed digitizing card (20 MSamples/second) would be used along with diskless and fanless industrial computer, powered by the solar panel.

It is planned to use WiFi or GPRS / EDGE / UMTS / HSPDA communication between remote sites and the control centre.

## 8 CONCLUSIONS

1. Lightning rods installed on the tower tops of the double circuit, vertical configuration compact unshielded line reduce line flashover rate. This reduction depends on the tower footing resistance values and lightning rod heights
2. By the installation of the LSA on the top conductor only, line flashover rate is substantially improved (for the considered line flashover rate is zero for the tower footing resistance up to 20 Ω).
3. In the case of the unshielded line, lightning strokes are hitting directly phase conductors on which LSA are installed. Shape of the LSA lightning current is similar to the shape of the original lightning stroke. These are the main reasons for the high-energy duties of the LSA installed on the unshielded lines.
4. When short lightning rods are installed on the tower tops, ‘high-energy’ strokes are hitting directly lightning rods.
5. The added lightning rods substantially decrease LSA current peaks. LSA current peaks are almost three times reduced, even for the 1 m long (short) rod.
6. There is a substantial LSA energy duty reduction by the installation of the lightning rods. This reduction depends mainly on the value of tower footing resistance (may be forty times for 5 Ω resistance).
7. With the LSA energy duty reduction by the installation of the short lightning rods on the tower tops, we can use LSA of lower IEC Class (for example distribution class LSA instead of IEC Class II or III). Distribution class LSA are lighter, easier to install and much cheaper.
8. In order to verify results obtained in this study it is planned to develop the corresponding pilot project. The main idea is to install the real time monitoring equipment for the LSA and lightning rods current shapes monitoring.

## 9 REFERENCES


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