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# Lightning Performance Assessment to Improve Lightning Protection System of 115 kV Overhead Lines

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## ABSTRACT

This paper determined suitable lightning performance indices for a lightning protection system of 115 kV overhead distribution lines for the cases before and after improvement with seven types of line configuration, following the construction standard of the Provincial Electricity Authority (PEA). The shielding failure flashover rate (SFFR) caused by a lightning strike to the line phase due to shielding failure, the back flashover rate (BFR) due to a direct strike on an overhead ground wire, and the total flashover rate(TFR) were used as lightning performance indices. The outage rate caused by lightning could be reduced by lightning performance improvement. This paper considered improvement and flashover rate analysis from lightning using five methods: reducing footing resistance, increasing the number of suspension insulators, increasing the diameter of the down conductor, reducing the shielding angle and installing a surge arrester on the lowest phase conductor. The analysis showed that before the improvements were implemented, the total flashover rate of several overhead distribution line arrangements was about 13-15 flashes/100 km/year and after the improvements were implemented, it was reduced to about 4-13 flashes/100 km/year.


**Keywords:** lightning performance, shielding failure flashover rate, back flashover rate

## INTRODUCTION

Safety, reliability and minimal investment in the distribution system are major goals of the Electricity Distribution Utility. An important cause of interruptions to service is outage from lightning. Lightning can strike an overhead ground wire, phased wires or an object on or near to the ground. In addition, it can create in-line overvoltage flows and flashover can occur by exceeding the rated voltage protection of the insulator. Design of a lightning protection system focuses on lightning striking a ground wire and the insulators being able to withstand the lightning current providing it is in a standard range. Secondly, a lightning strike on a phased wire could occur when there is shielding failure from an event with low lightning peak current. Thirdly, lightning strikes on an object on or near to the ground occur regularly and generate in-line induced voltage. Induced overvoltage would occur when there is either high lightning peak current or a lightning strike near a phased wire. When the voltage on the suspension insulator is greater than the insulator's rated voltage protection, flashover on the insulator surface occurs, resulting in an outage. However, overvoltage under such circumstances is usually the last possibility compared with the

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first two situations described above (Klairuang, 2003), because if the distribution system is constructed according to suitable standards, there should be no chance for a tree or object to get close to or contact lines and then create an overvoltage that the insulator could not withstand.

Thailand is situated in a tropical zone, where thunderstorms occur frequently and are more severe than in European countries. Consequently, the European standard, which has been used in the design of the lightning protection system in Thailand, is not effective. Where lightning is the major cause of outages in the distribution system, lightning protection system improvement should be a primary consideration to reduce the outage rate. This paper introduced a procedure and suitable solution to improve the lightning protection system for 115 kV distribution systems.

## MATERIALS AND METHODS

A lightning performance index was analyzed using various types of overhead distribution systems, following the construction standards of the Provincial Electricity Authority (PEA). Results were considered before and after implementing the lightning protection system improvements. The line configuration standards of the PEA for 115 kV structures are (Figure 1):

1) Single Circuit Double Conductor Tangent Structure TYPE SD-TG-3

2) Single Circuit Double Conductor Tangent Structure TYPE SD-TG-5

3) Single Circuit Double Conductor Tangent Structure TYPE SD-TG-8

4) Single Circuit Single Conductor Tangent Structure TYPE SS-TG-3

5) Single Circuit Single Conductor

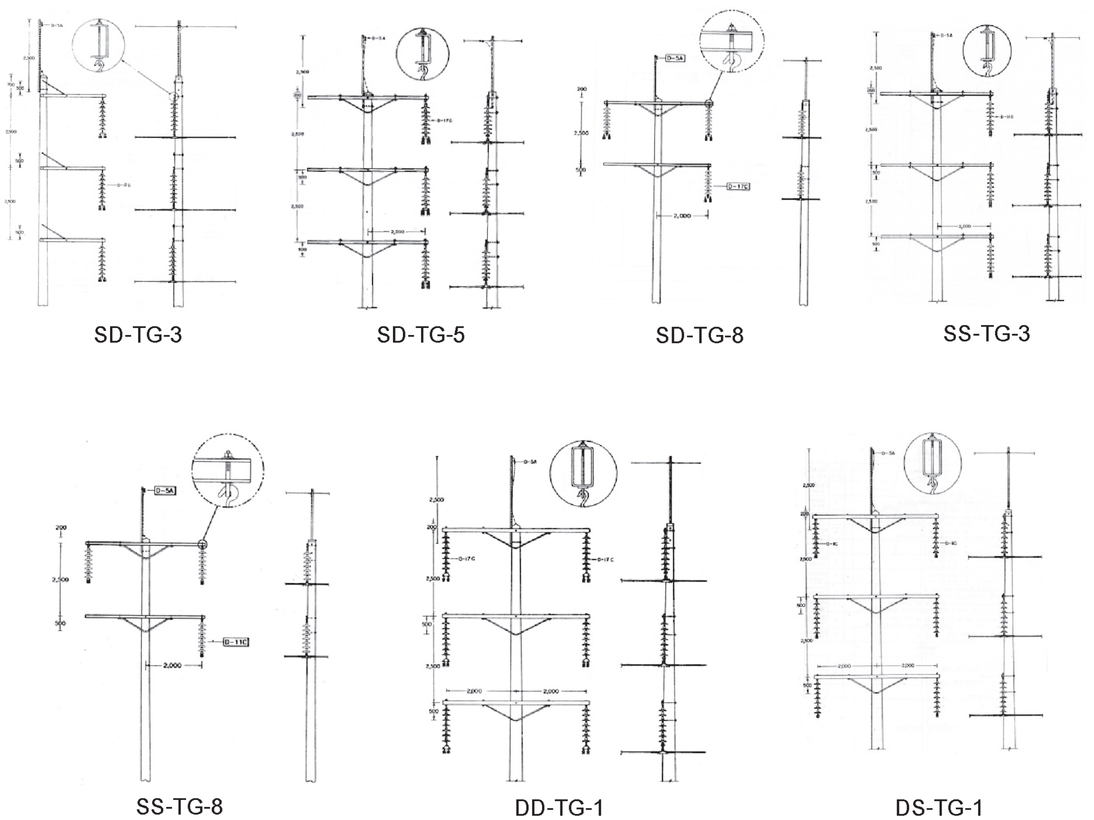


**Figure 1** Overhead line configuration standards for 115 kV PEA distribution systems.

Tangent Structure TYPE SS-TG-8

6) Double Circuit Double Conductor Tangent Structure TYPE DD-TG-1

7) Double Circuit Single Conductor Tangent Structure TYPE DS-TG-1

**Lightning performance indices**

Overvoltage can occur when lightning strikes an overhead distribution line. When the voltage on the insulator exceeds the maximum design voltage, an outage occurs. For the analysis of overvoltage in terms of lightning, a performance index was developed based on the striking position, which was considered to be the main factor to examine with regard to outage rates. Outage from lightning can be categorized according to lightning strikes on ground wires or on phased wires.

**Lightning strike on ground wires**

Insulators on overhead distribution systems have been designed to sustain overvoltage on an insulator created by a lightning strike on the ground wire. In cases where the voltage on an insulator exceeds the limit as a result of a strike by a very high lightning current, flashover on the insulator surface occurs from the ground wire back to the phase wire. Analysis could find the maximum lightning current that a suspension insulator could bear or adjust the overvoltage on the insulator to the level of the critical flashover voltage. The critical flashover voltage could be evaluated using the ATPDraw computer software.

Critical lightning peak current analysis was undertaken using lightning statistic data in Thailand. There are 60 days of thunderstorms in Thailand annually (Thai Meteorological Department, 2006). The probability of a lightning strike of different lightning currents is shown by Equation 1 (IEEE Standard 1410, 2004), based on the lightning location system (LLS) from the Electricity Generating Authority of Thailand (EGAT). The average lightning peak current ($I_{50}$) is 20 kA. The number of lightning strikes directly to the ground and to overhead wires could be determined by Equations 2 and 3, respectively and the back flashover rate by Equation 4.

$$P\left(I \geq i_0\right) = \frac{1}{1+\left(\frac{i_0}{I_{50}}\right)^{3.09}} \tag{1}$$

$$N_g = 6.5\times10^{-5}T_d^{2.277} \tag{2}$$

$$N_L = N_g\left(\frac{28h^{0.6}+b}{10}\right) \tag{3}$$

$$BFR = N_L P(I \geq Ic) \tag{4}$$

where: $P(I \geq i_0)$ = Probability of lightning peak current over $i_0$

$I_{50}$ = Average lightning peak current (kA)

$N_g$ = Number of lightning strikes directly to ground (flash/km$^2$/year) (Samitthileela, 1999)

$T_d$ = Number of thunderstorm days per year

$N_L$ = Number of lightning strikes on wires (flash/100 km/year) (IEEE Standard 1243, 1997)

$h$ = Height of pole (m)

$b$ = Structure width (m)

$BFR$ = Back flashover rate (flash/100 km/year)

$P(I \geq Ic)$ = Probability of lightning peak current exceeding critical peak current $I_c$

**Lightning strike on phase wires**

A ground wire protection system is installed in a distribution system to prevent lightning from striking directly onto phase wires. Lightning protection performance would depend on the line arrangement or the protection angle. Shielding angle failure could occur from a low lightning peak current, with the lowest striking distance (S) or radius of the rolling sphere which was protected by the ground wire being determined from the line configurations in Figure 1 with Equations 5 and 6.

$$S = \frac{1}{2}\left[H_G + H_P + \frac{A(2W - A)}{H_G - H_P}\right] \quad (5)$$

$$W = \frac{H_G A + \sqrt{H_G H_P \left(A^2 + (H_G - H_P)^2\right)}}{H_G - H_P} \quad (6)$$

where: $S$ = Critical striking distance for effective ground wire (m)

$H_G$ = Height of ground wire (m)

$H_P$ = Height of phase wire (m)

$A$ = Horizontal distance between ground wire and phase wire (m)

Table 1 represents the findings on striking distance by various authors that can be used to determine the striking distance for the critical lightning peak current against which the ground wire could protect the phase wire. The shielding failure flashover rate (SFFR) can then be used to determine the minimum performance parameters for the ground wire (Equation 7):

$$SFFR = N_L(P(I < I_P))(P(I > I_C)) \quad (7)$$

where: $I_P$ = Critical lightning peak current that protection with ground wire (kA)

$I_C$ = Critical lightning peak current from lightning directly to phase wire (kA)

SFFR = Shielding Failure Flashover Rate (flashes/100 km/year)

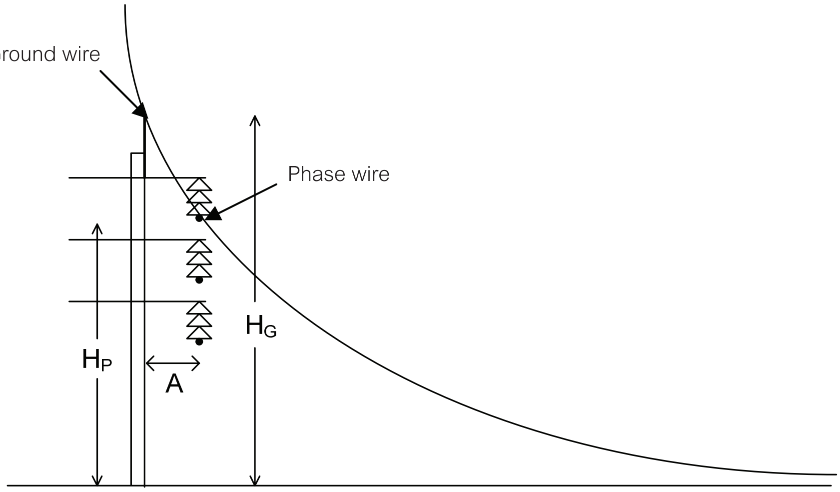


**Figure 2** Critical striking distance, where the ground wire could prevent a direct strike on the phase wire.

**Table 1** Relationship between striking distance ($S$) and lightning peak current ($I$) (Hileman, 1999).

| Source | Parameters ($S = KI^B$) | |
|---|---|---|
| | $K$ | $B$ |
| Armstrong and Whitehead | 6.7 | 0.8 |
| Brown and Whitehead | 7.1 | 0.75 |
| Wagner | 14.2 | 0.42 |
| IEEE-1992 | 10.0 | 0.65 |
| Love | 10.0 | 0.65 |
| Berger (negative lightning) | $S^- = I + 15(1 - e^{-0.15I})$ | |
| (positive lightning) | $S^+ = 1.5I + 20(1 - e^{-0.15I})$ | |

Striking distance is defined by $S = KI^B$, where $S$ = lightning striking distance (m), $I$ = lightning peak current (kA), and $K$ and $B$ are constant values.

**Lightning performance improvement**

The lightning outage rate could be reduced by lightning performance improvements or by increasing the insulation level. This paper considered improvements to lightning performance and flashover rate analysis from lightning using five methods: 1) reducing grounding resistance of the footing pole from 5 ohms to 2 ohms; 2) increasing the number of suspension insulators from 7 to 8 insulators; 3) increasing the diameter of the down conductor from 50 $mm^2$ to 95 $mm^2$ ; 4) reducing the shielding angle by increasing the number of ground wires from 1 to 2 lines; and 5) installing a surge arrester on the lowest phase at 200 m intervals.

## RESULTS AND DISCUSSION

The maximum lightning current for the case of a lightning strike on the ground wire is shown in Table 2. The results show that a lightning strike to the top of the pole, which happens frequently on higher ground, could produce a lower critical current than a lightning strike to the phase wire. Thus, the flashover rate was only considered for a lightning strike to the top of pole.

The critical lightning peak current with ground wire protection can be calculated from the equations in Table 1. The critical lightning peak current, in the case of lightning striking the phase conductor and then creating flashover on the insulator surface, can be analyzed with ATPDraw. Results from the analysis and the shielding failure flashover rate (SFFR) determined from (7) are shown in Table 3.

The back flashover and shielding failure flashover rates for the different structures were almost identical, with approximately 13 flashes/100 km/year and 1.5 flashes/100 km/year respectively. A double circuit double conductor structure would provide a greater flashover rate than the other configurations.

**Table 2** Critical lightning current in case of lightning strike on ground wire.

| Line configuration | Critical lightning peak current, *Ic* [kA] | |
|---|---|---|
| | Strike to top of pole | Strike to middle span |
| SD-TG-3 | 80.10 | 90.42 |
| SD-TG-5 | 80.10 | 90.42 |
| SD-TG-8 | 81.53 | 88.09 |
| SS-TG-3 | 80.34 | 91.20 |
| SS-TG-8 | 81.53 | 88.09 |
| DD-TG-1 | 78.07 | 83.79 |
| DS-TG-1 | 78.17 | 83.63 |

**Table 3** Lightning performance indices (shielding failure flashover rate (SFFR), back flashover rate (BFR) and Total flashover rate (TFR) before improvements (flashes/100 km/year).

| Line configuration | SFFR | BFR | Total flashover rate (TFR) |
|---|---|---|---|
| SD-TG-3 | 1.01 | 12.72 | 13.73 |
| SD-TG-5 | 1.80 | 12.41 | 14.21 |
| SD-TG-8 | 1.56 | 12.11 | 13.67 |
| SS-TG-3 | 1.48 | 12.32 | 13.80 |
| SS-TG-8 | 1.30 | 12.02 | 13.32 |
| DD-TG-1 | 1.80 | 13.61 | 15.41 |
| DS-TG-1 | 1.48 | 13.56 | 15.04 |

**Table 4** Lightning performance index before and after improvements (flashes/100km/year).

| Line | Total flashover rate (TFR) | | | | | |
|---|---|---|---|---|---|---|
| Configuration | Before | Method 1 | Method 2 | Method 3 | Method 4 | Method 5 |
| SD-TG-3 | 13.73 | 9.73 | 10.20 | 13.57 | - | 5.28 |
| SD-TG-5 | 14.21 | 10.27 | 10.76 | 14.05 | - | 5.83 |
| SD-TG-8 | 13.67 | 11.59 | 10.30 | 13.50 | 11.84 | 6.18 |
| SS-TG-3 | 13.80 | 9.43 | 10.40 | 13.67 | - | 6.25 |
| SS-TG-8 | 13.32 | 11.25 | 9.97 | 13.14 | 11.49 | 6.95 |
| DD-TG-1 | 15.41 | 13.10 | 11.68 | 15.24 | 13.92 | 3.99 |
| DS-TG-1 | 15.04 | 12.79 | 11.32 | 14.86 | 13.49 | 4.19 |

**Note:** Methods are described in the text. Additional ground wire installation (Method 4) was not necessary for the one-sided conductor systems.

Without taking into account the cost of investment, different structures required different techniques to improve the flashover rate. According to Table 4, neglecting the surge arrester installation methods for the SD-TG-3, SD-TG-5 and SS-TG-3 structures would be appropriate with the grounding resistance reduction method. Increasing the insulation level was a proper option for the SD-TG-8, SS-TG-8, DD-TG-1 and DS-TG-1 structures. Increasing the diameter of the down conductor and adding to the number of ground wire methods would not reduce the flashover rate as much as other methods. Surge arrester installation was the best option to reduce the flashover rate by making a high investment.

## CONCLUSION

The results of the analysis of the lightning performance indices on a 115 kV overhead distribution system with all seven line configurations using the five improvement methods showed that:

1) The back flashover rate on the surface results from a lightning strike to the ground wire. The double circuit structure was the worst option to reduce the back flashover rate.

2) The flashover rate caused by shielding angle failure on each structure was almost identical to 2 flashes/100 km/year due to the symmetry of alignment between the ground wire and the top-phase wire.

3) The best overall lightning performance index was the total flashover rate caused by lightning before improvement. This index was almost indistinguishable for each structure, which was 13-15 flashes/100 km/year before any improvement method was applied.

4) Increasing the diameter size of the down conductor was method that produced the minimum improvement to performance.

5) There were several methods that improved lightning performance. The best option from the analysis was to install a surge arrester on the bottom phase at 200-m intervals.

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