Investigation of Lightning Trip-out on 150kV Transmission Line in West Sumatra in Indonesia

静岡大学博士論文

Investigation of Lightning Trip-out on 150kV Transmission Line in West Sumatra in Indonesia
インドネシア西スマトラの 150kV 送電線雷トリップアウトに関する研究

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2017 年 6 月

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Abstract

The lightning performance on the 150 kV transmission line in West Sumatra in Indonesia is presented. It is shown that main cause of the trip-outs is lightning, 66% of all trip-outs. Main conclusions are as follow:

The trip-out rates calculated by taking account of the reduction of the tower-footing resistance due to the ionizing effect agree well with the observed ones. This indicates the importance of the impulse resistance in the analysis of the lightning performance of the line.

The trip-out rate at the lower arm is high for the cases of the average grounding resistance of 33.3 ohms, and the rates at the upper arm are high for the cases of the average grounding resistance of 5.6 ohms. Such trend can be simulated by the IEEE method using the impulse resistance.

The trend that trip-out ratio becomes high with the increase of the span length is significant after improvement of the tower-footing resistance. However, the trend is weak before improvement of the tower-footing resistance. This is because in the case of the high tower-footing resistance the flashover occurs before the arrival of the wave reflected from the adjacent towers due to the high potential rise of the tower. Therefore, the degree of the influence of the span length on the trip-out ratio is dependent on the tower-footing resistance.

The local lightning activity significantly affects the trip-out rate. The high rate of lightning trip-out before and after the improvement of the tower-footing resistance is seen in circuit I. This is due to the placement of circuit I on the north side from No. 1 to 37 towers and on the east side from No. 38 to No. 140 towers. In this area, the thunderstorm often approaches the line from the northeast.

The trip-out rate of the line under study can be reduced to less than half of the present rate, 22 flashover/100 km–year, if the tower-footing resistance at all towers is set to less than 10 Ω and the length of an arcing horn gap is set to longer than 1.2 m.

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Introduction

1.1 Research background

An electric power transmission system in Indonesia more commonly uses an overhead line than an underground cable. An overhead transmission line is quite susceptible to lightning strokes due to high construction. There is a 150 kV transmission line from Payakumbuh to Koto Panjang in West Sumatra, passing the area whose average number of thunderstorm days per year (IKL: Isokeraunic levels) reached up to 165, and the frequency of direct lightning strokes to the transmission line was high. This line is the trunk line between West Sumatra sub-system (Padang UPT) and Riau sub-system (Riau UPT). The intensity of a lightning stroke is very high, due to the layout of the transmission line that is surrounded by mountain, hill and near the sea[1-2]. Thus, they had a threat of lightning from the sea and the lines that cross the mountain and hill are structures that appear on the surface of the ground and become an easy target for lightning stroke. Therefore, it must have a high degree of immunity against lightning strokes.

According to the data from the Distribution and Load Control Centre Sumatra (Sumatra P3B), the main cause of the trip-outs is lightning, amounting to 66% of all trip-outs [3-5]. In addtion to causing blackouts, lightning overvoltage also causes the trip-out of the transmission line.

An example of these incidents is the Payakumbuh–Koto Panjang blackout that lasted as long as 10 minutes in 2010. In 2011, the blackout is also caused by the outage of Circuit 1 and 2 for 39 and 57 minutes, respectively [3-5].

Lightning performance of a transmission line has been studied for a long time. According to [6-8], the high ratio of trip-outs of 110 kV to 138 kV lines in

China, Mexico, and Malaysia for five years were 62%, 50%, and 79%, respectively. In Japan, the high ratio of lightning trip-outs of 110 – 154 kV lines was 75% [9].

Lightning trip-outs mean the operation of a circuit breaker at the substation due to flashover caused by lightning [10]. Furthermore, it is shown that the tower-footing resistance has a significant influence on the back-flashover protection performance: the lower the tower-footing impedance, the less the back-flashover rate [10-18].

1.2 Problem statement

In this thesis, lightning performance of the 150 kV transmission line in West Sumatra is studied. To the best of our knowledge, this is the first time that the lightning performance of the transmission line in West Sumatra high lightning activity area and the high lightning trip-out area is studied. In fact, the overhead line located in hilly areas will be much closer to the clouds, thus having more frequency of lightning strokes. West Sumatra is located in a tropical area. Therefore, the air has a humidity, which explains the high-intensity lightning in Figure 1.1, namely 20 to 40 flashes/100 km-year [19] for high isokeraunic level area. According to [20] the lightning trip-out rate of 110 kV to 154 kV line from 1980 to 2000 was 1.7 to 2.8 trip-out/100 km-year. There is a 150 kV transmission line from Payakumbuh to Koto Panjang in West Sumatra, passing an area whose average number of thunderstorm days per year (IKL: Isokeraunic levels) reached 165, and the possibility of direct lightning strokes to the transmission line, including the strokes to the transmission tower, is high [3-5]. The location of the transmission line under study in West Sumatra is shown in Figure 1.2 as the blue line. Among 248 towers, 156 towers (63 %) are located on hills, 51 towers (20.5 %) in rice fields, and 41 towers (16.5 %) in the forest [1,21].

1.3 Research objectives

The purpose of the study is to achievement the stable power supply, which is indispensable in maintaining a comfortable life.

In this thesis, an investigation of a lightning trip-out of a 150 kV transmission line in West Sumatra in Indonesia is carried out. To improve the lightning protection design of the transmission line, the followings are the targets:

1. The impact of tower-footing resistance to the number of trip-out rates.
2. The impact of length of arcing horn gap to the number of lightning trip-out rates.
3. A tower-footing resistance value for accurate estimation of the lightning performance of the transmission line under study.
4. Proper arcing horn gap on the transmission line under.

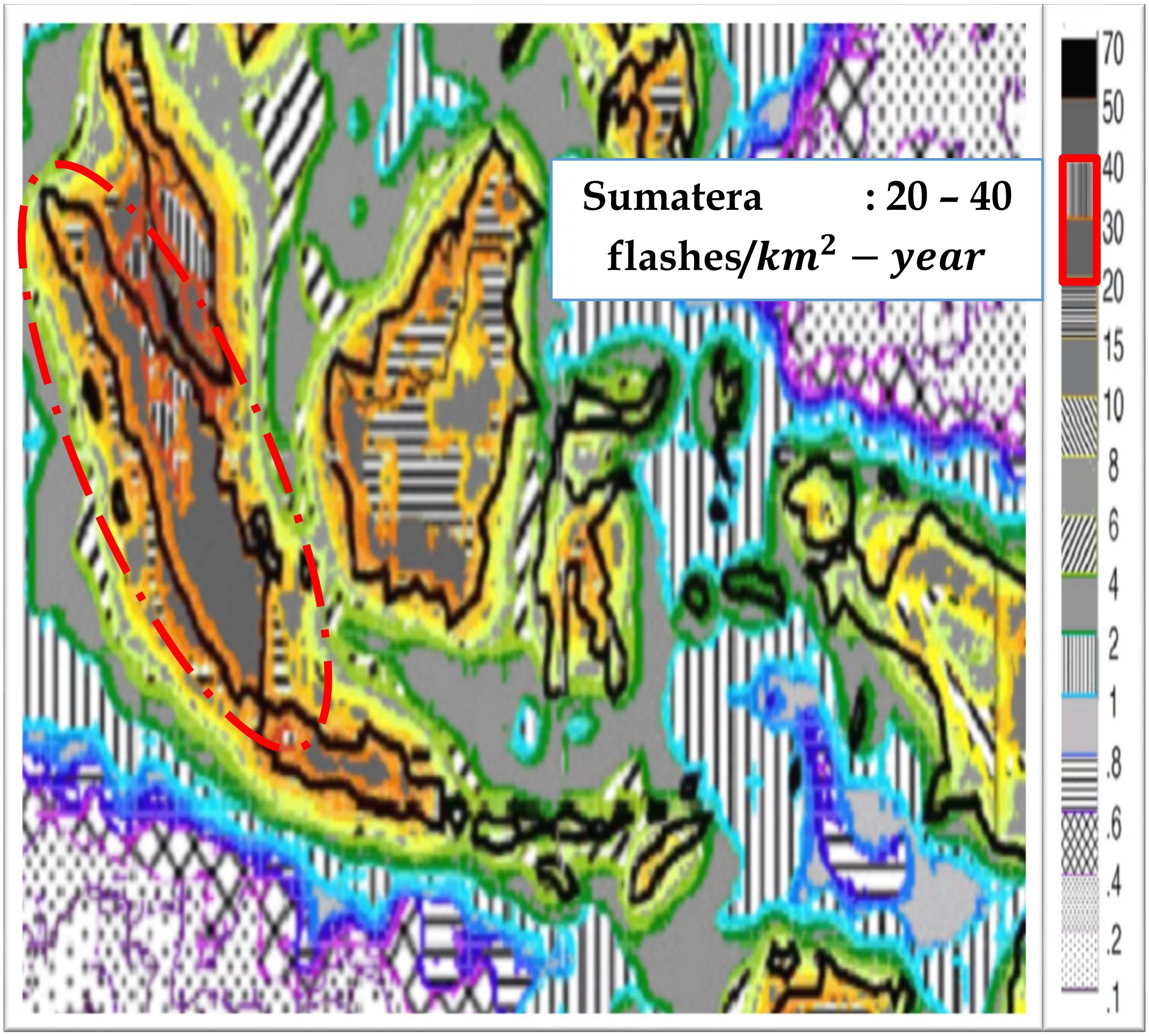

Fig. 1.1 Lightning Flash Density [19].

Fig. 1.2 Location of Transmission line under study in West Sumatra [20].

1.4 Novelty

The novel aspects of the thesis are as follows:

1. The first time that the lightning performance of the transmission line in West Sumatra with the high lightning activity and high lightning trip-out rate is studied.
2. After improvement of tower-footing resistance, the trip-out rate due to the average tower-footing resistance at the low frequency by IEEE Flash program well agree with the observation results in this case the impulse resistance is almost equal to average tower-footing resistance at low frequency.
3. The trip-out rates calculated by taking into account the reduction of the tower-footing resistance due to the ionizing effect well agree with the observed results.
4. The trip-out rate on the lower arm is high in the cases of the high tower-footing resistance.

1.5 Thesis Outline

This thesis consists of 6 chapters stated as follows:

In Chapter 2, a brief overview of issues related to the lightning performance of a transmission line is presented. These are on the effect of the tower-footing resistance, computation of tower top voltage, calculation of cross arm voltages, calculation of insulator voltages, comparison of insulator voltage with the voltage-time curve and reflection from adjacent towers.

In Chapter 3, investigation results are presented. The lightning trip-outs of the transmission line under study and tower-footing resistance are investigated. The factors influencing lightning trip-outs (span length, the altitude of towers, the height difference of tower top and the length of an arcing horn gap) and flashover location are discussed.

In Chapter 4, the method of analysis is explained. To estimated the lightning trip-out rate, the analytical two-point method is used. IEEE FLASH program are also used.

In Chapter 5, the results of numerical simulations are presented. The results are in reasonable agreement with the observed results.

In Chapter 6, the conclusions of the study and suggestions for future work are shown.

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2

Literature Review

2.1 Overview

In this chapter references related to the lightning trip-out on the transmission line are reviewed as well as the effect of parameters on the number of lightning trip-out on the transmission line. This section provides essential and valuable background information for the following chapter. Furthermore, the final chapter focuses on the effect of parameters on the number of lightning trip-out on 150 kV transmission line under study.

2.2 Lightning parameter

The basic concepts that appear in any computation of lightning flashover of transmission line divide broadly into the concepts of incidence (the occurrence of lightning on the line) and the concepts of response (the voltages created on the line by the lightning). Knowledge of the former relies primarily on incidental observations and inferences both from records and from field measurements [1].

2.2.1 Keraunic levels and isokeraunic maps

Any locality through which transmission lines must pass may be said to have a particular keraunic level or isokeraunic level, as it is usually called. The level represents the average number of thunder-days per year in that locality, namely the average number of days per year on which thunder will be heard during a 24-hour period [1].

The keraunic level is a statistic that obviously depends on the hearing ability of the weather observers and on ambient noise background and local geography. If thunder is heard on any one day more than one time, the day is still classified as one thunder-day (or thunderstorm day) [1].

The keraunic level is the first statistic that must be known for a given geographical region before the lightning incidence to the earth and to any transmission line in that area can be computed. In a first approximation, an error in determining this important parameter will cause a proportional error in the calculation of lightning performance.

Figure 2.1 shows a map of the IKL of West Sumatra and the location of a 150 kV overhead transmission line between Payakumbuh and Koto Panjang under study, shown as the solid line in the middle. Thunderstorm-days for a year were as many as 165 in the area where tower No. 1-140 are located [2-3]. The tropical climate in Indonesia causes high lightning activity every year.

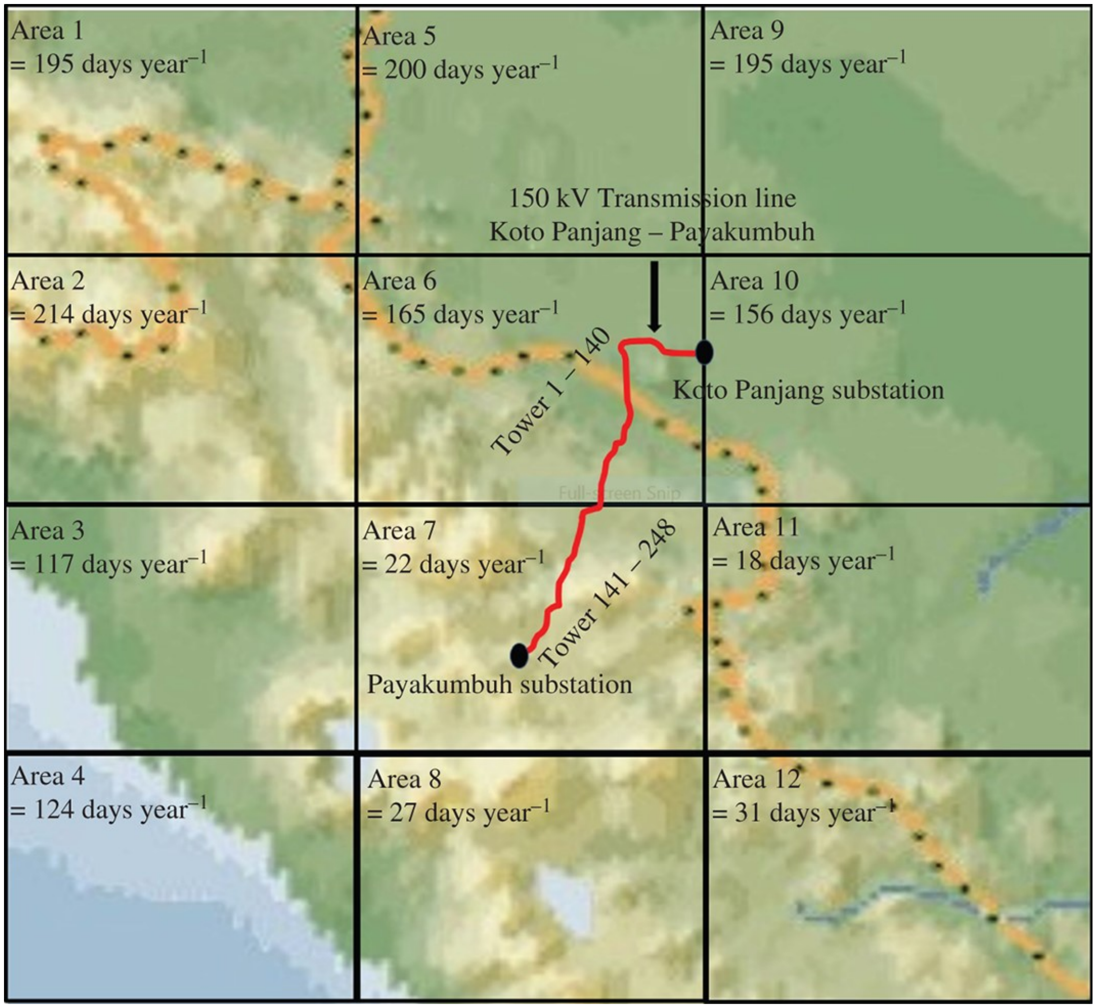


Fig. 2.1 Map of Isokeraunic Level [2-3].

2.2.2 Ground flash density

For simplicity, it has usually been assumed that the number of flashes to the earth or a transmission line in a particular locality is roughly proportional to the keraunic level (annual thunder-days) in that locality. A comprehensive summation of the research on relationships between flash counts to the earth and the keraunic level is presented [4]. Table 12.4.1, (taken from [4]) show that the number of ground flashes/km^2/year is proportional to the factor of 0.1 T to 0.19 T, where T is the keraunic level in annual thunder-days. If thunderstorm days are to be used as a basis, the following equation (2.1) is suggested [1.4,5];

$$N = 0.12\,T \tag{2.1}$$

where N is the number of flashes to earth per square kilometer per year and T is the keraunic level in thunder-days per year in the area.

The regional incidence of lightning in the area is defined by the annual average ground flash density, Ng (flashes/km^2-year). The lightning outage rate is linearly affected by the lightning flash density. In 1980, there was a significant improvement in the measurement of N_g. In [5], Eriksson proposes equation (2.2). This equation has been accepted by both CIGRE and IEEE [1,5,6].

$$N_g \;=\; 0.04\,TD^{1.25} \tag{2.2}$$

where, N_g is the ground flash density, flashes/km^2-year, TD is thunderstorm-day.

2.2.3 Lightning incidence to overhead lines

Anderson [1,5,6] implemented a height-dependent conductor shadow width to establish the stroke rate to an overhead wire. Equation from (2.3) from Eriksson in [5] is used to estimate the number of strokes to a line with tower height h_t.

$$N_s = \frac{N_g}{10}(28h_t^{1.09} + b) \qquad (2.3)$$

where N_s is flashes /100 km-year, N_g is ground flash density, flashes/km^2-year, b is overhead ground wire separation distance (m), and h_t is tower height (m).

Eriksson's model depends only on tower height while the others are derived from average conductor height, a function of both tower height and sag [5,6,7,8,9].

2.2.4 Probability distribution of stroke amplitudes

The probability of lightning striking a particular object situated on the earth (ground) is found by multiplying the object's lightning-attractive area by the local ground flash density (lightning strikes to ground per km^2 per year). These possibilities become clear each year as the increasing volume of data on the stroke current amplitudes from various research projects is reported [1].

For lightning flashover computing using a little calculation, the statistical log-normal curve is much too complicated, but these log-normal curve may be approximated with entirely reasonable accuracy between 5 kA and 200 kA with two simple equations, namely Popolansky curve in (2.4) and Anderson – Eriksson curve in (2.5)

$$P_I = \frac{1}{1+\left(\frac{I}{25}\right)^2} \qquad (2.4)$$

$$P_I = \frac{1}{1+\left(\frac{I}{31}\right)^{2.6}} \tag{2.5}$$

where P_I is the probability that the peak current in any flash will exceed I in (kA). Equation (2.5) is used as the basic for all stroke-current magnitude calculation for back-flashover [1,6,9,10,11]. Therefore, (2.5) is adopted in this study.

2.2.5 Effective radius of shield wire and phase conductors with corona

The corona envelope may be over a meter in diameter and its effect on the voltages induced on the phase conductors may be very significant. Similarly, for a phase conductor, the corona envelope that forms when a flash contacts the phase conductor directly may be sufficiently large to help limit the overvoltage and improve the lightning performance.

The corona envelope is assumed to be a cylinder and symmetrical and to progress outward until the gradient, E_o, at its surface falls to the same value insufficient to sustain further propagation.

The electrical coupling effect of conductors with corona envelopes varies more or less with the logarithm of the radius, so even a rough approximation will usually be adequate. The resulting Equation is [1,11,12]

$$R\, ln\frac{2h_t}{R} = \frac{V}{E_o} \tag{2.6}$$

where R is the radius of the corona envelope (m), h_t is the height of the conductor above ground (m), V is the voltage applied to the conductor (kV), and E_o is the limiting corona gradient below which the envelope can no longer grow (kV/m).

A plot of corona sheath diameters as a function of difference of the voltage applied to the conductor with the limiting corona gradient below which the envelope can no longer grow (kV/m) and $h = h_t$ is shown in Figure 2.2.

The envelope radius, R, is strongly influenced by the value of E_o. In [1,4,9,10] it is suggested the value of 1500 kV/m (15 kV/cm), the critical gradient for shield wires, should be about 20 kV/cm because of the shielding effect of the tower and 12 kV/cm for the phase conductors because of the attractive effects of the tower. However 15 kV/cm is a reasonable average value, and it is utilized in all subsequent calculation.

The effective radius of a single conductor should be taken as the geometric mean of its effects with and without the corona envelope. Therefore, the self-surge impedance of a single conductor in heavy corona is given by (2.7);

$$Z_{nn} = 60 \sqrt{ln\frac{2h_t}{r} ln\frac{2h_t}{R}} \tag{2.7}$$

where Z_{nn} is the self-surge impedance of conductor n (Ω), h_t is the height of conductor above ground (m), r is the radius of the metallic conductor (m), and R is the radius of the corona sheath around the conductor (m). For a bundle conductor, the presence of multiple sub-conductors causes a major reduction in the effective corona diameter of each sub-conductor [1,11,12].

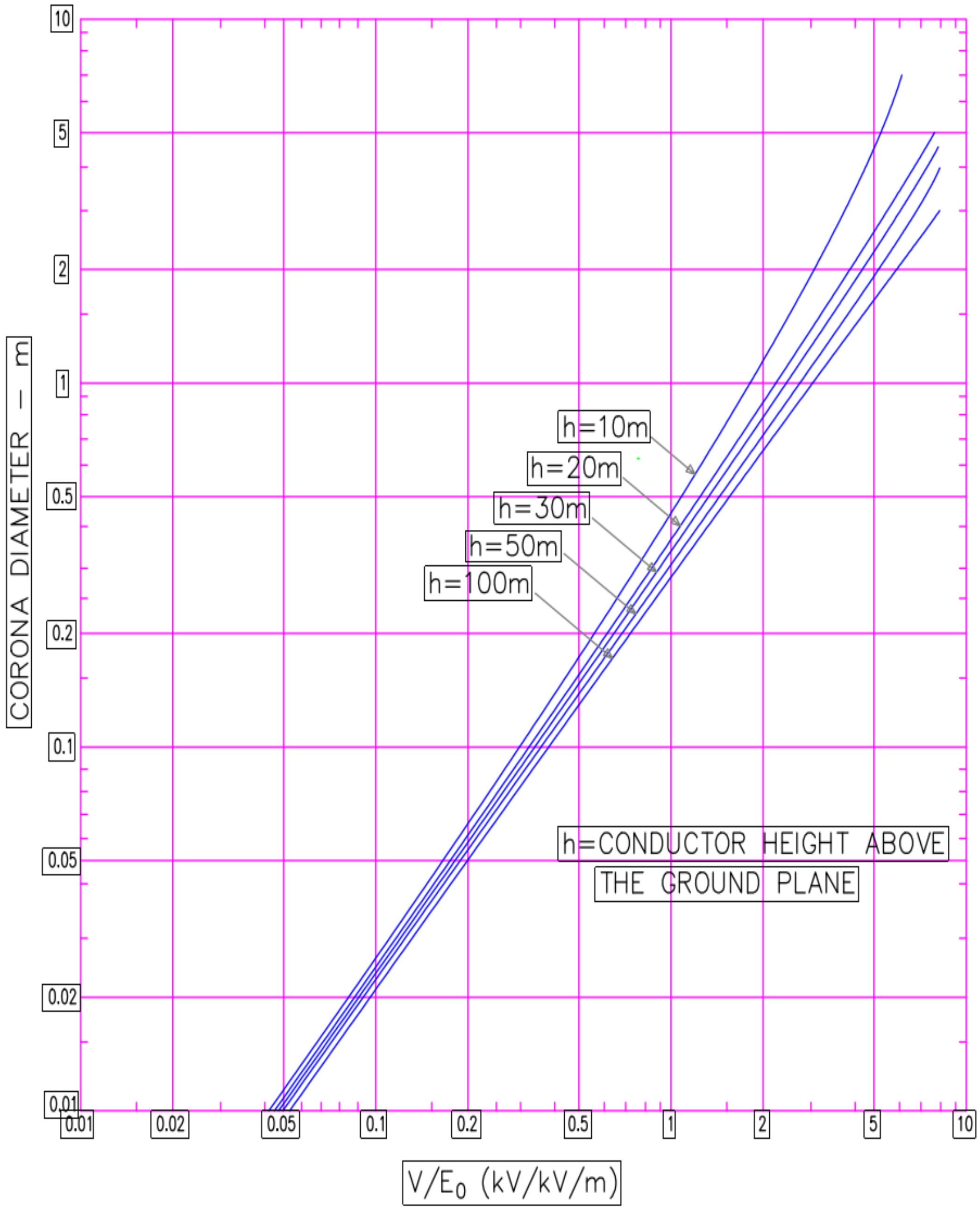


Fig. 2.2 Approximate diameter of the corona sheath around a conductor at high voltage [1].

2.2.6 Reduction of shield wire surge impedance to equivalent single-wire surge impedance

The self-surge impedance of a single conductor is the ratio of the voltage to the current in the conductor as a wave travels along it. The standard formula for this surge impedance for a conductor n parallel to earth is [1];

$$Z_{nn} = 60\ (\frac{4h_n}{D_n}) \tag{2.8}$$

where D_n is the effective diameter of conductor n. The mutual impedance between the two shield wire, Z_{mn} is;

$$Z_{mn} = 60\ (\frac{a_{mn}}{b_{mn}}) \tag{2.9}$$

where a_{mn} is the distance from conductor m to the image of conductor n in the earth and b_{mn} is the direct distance between conductors m and n, a_{mn} and b_{mn} are defined in Figure 2.3.

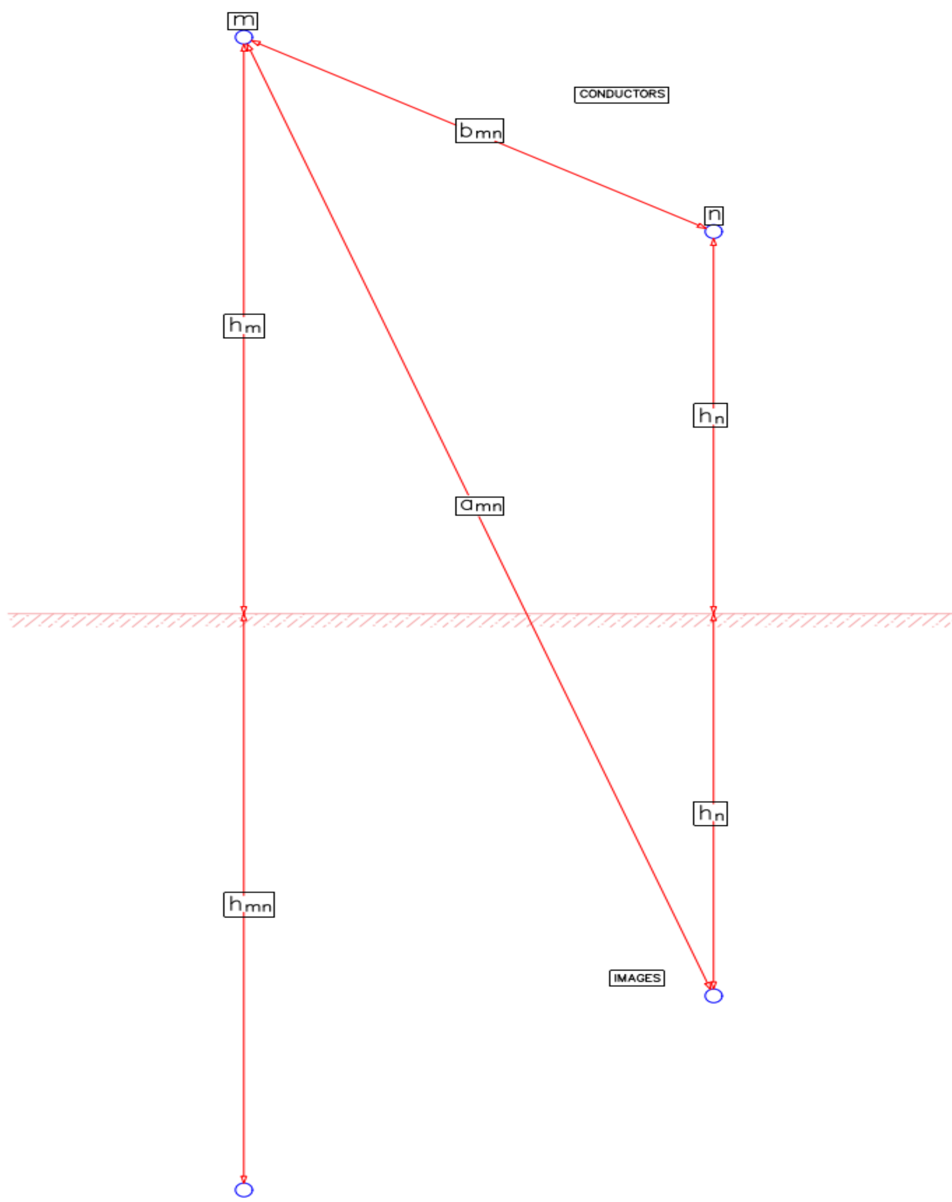


Fig. 2.3 Distance evolved in computing mutual impedances between two conductors [1].

The equivalent surge impedance of two shield wires (connected to the same level of the tower is;

$$Z_s = \frac{Z_{11}+Z_{12}}{2} \tag{2.10}$$

where Z_{11} is the self-surge impedance of one of the shield wires and Z_{12} is the natural surge impedance between conductor 1 and conductor 2.

2.3 Tower-footing resistance

In practice, a transmission line does not have a constant value of tower-footing resistance but has a range of values depending on tower location.

The soil ionization and the breakdown characteristics of the ground surrounding the tower grounding electrodes affect the magnitude of tower footing resistance, which is not constant and varies according to the surge current magnitude. The impulse grounding resistance is less than the grounding resistance values measured at low current and low frequency. This is because particular voltage gradients, sufficient to break down the soil, create conductive paths for the current; as a result, the grounding resistance is reduced. The relationship between impulse and non-impulse grounding resistances can be shown as in Equation (2.11) [11,12],

$$R_i = \frac{R_o}{\sqrt{1+\left({I_R}/{I_g}\right)}} \tag{2.11}$$

where R_i is the impulse tower-footing resistance (Ω), R_o is the tower-footingresistance at low current and low frequency (Ω),I_R is the surge current into the ground (kA), I_g is the limiting current initiating soil ionization (kA) as given in the Equation (2.12);

$$I_g = \frac{1}{2\pi} \frac{E_o \rho_o}{R_i^2} \tag{2.12}$$

where ρ_o is the soil resistivity (Ωm), E_o is the soil ionization gradient (about 300 kV/m).

2.4 Response of a transmission tower to a lightning flash

2.4.1 Computation of tower surge impedance

The accurate representation of the tower in the calculation of lightning voltage on transmission lines is very important for simulation results of lightning overvoltage. The results of the geometric model studies indicated that the tower element might be conveniently and accurately represented as a transmission line of constant surge impedance. The towers can be represented by simple geometric figures such as a cylinder, cone or double cone [1,11,13,14,15,16,17].

The tower surge impedances for a variety of shapes (Class 1, Class 2 and Class 3) in Figure 2.4 are calculated by the following formulae (2.13, 2.14 and 2.15), respectively:

$$Z_t = 30\, ln \left[\frac{2({h_t}^2 + r^2)}{r^2}\right] \tag{2.13}$$

$$Z_t = 1/2(Z_S + Z_m) \tag{2.14}$$

$$Z_S = 60 \ln\left(\frac{h}{r}\right) + 90 \left(\frac{r}{h}\right)) - 60 \tag{2.14a}$$

$$Z_m = 60 \ln\left(\frac{h}{b}\right) + 90 \left(\frac{b}{h}\right)) - 60 \qquad (2.14b)$$

$$Z_t = 60\left[ln\left(\sqrt{2}\,\frac{2h}{r}\right) - 1\right] \qquad (2.15)$$

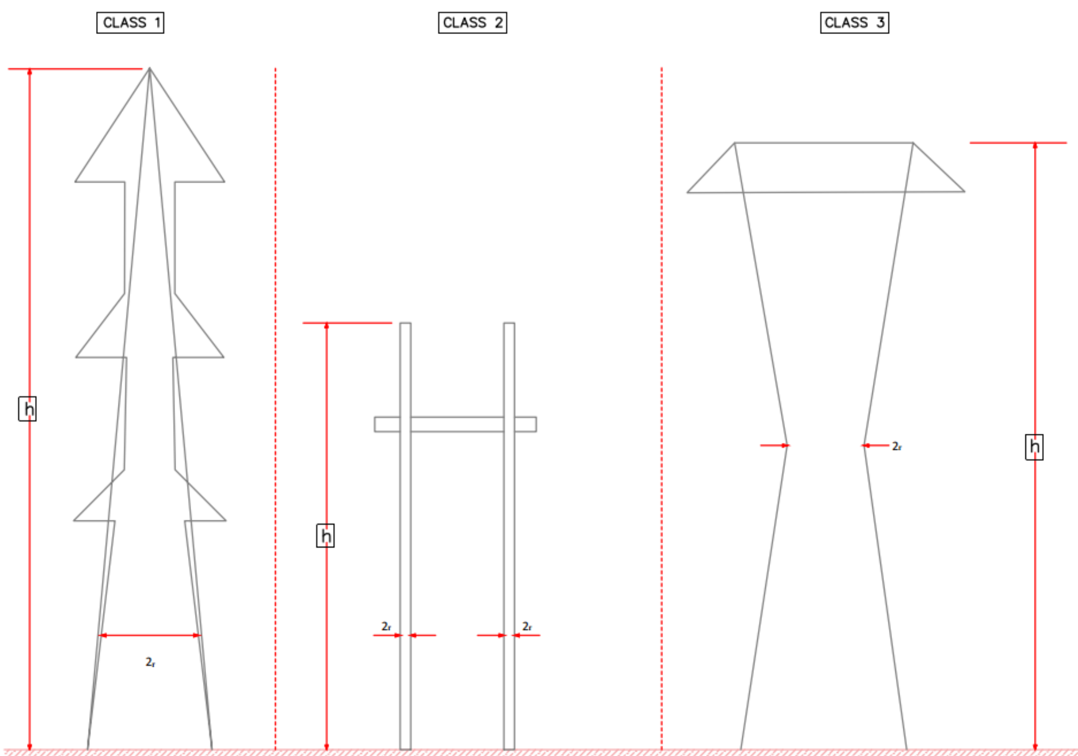


Fig. 2.4 Approximation for tower surge impedance [1].

2.4.2 Computation of coupling factor for phase conductors

That portion of the stroke current flowing outward over the shield wires induces a voltage called the coupled voltage in each phase conductor, and the ratio of the total induced voltage on phase conductor n to the tower top voltage is known as the coefficient of coupling, K_n. It is expressed for the case of two shield wires at equal height above ground as;

$$K_n = \frac{Z_{n1} + Z_{n2}}{Z_{11} + Z_{22}} \tag{2.16}$$

where Z_{mn} is the natural mutual impedance between conductor m and n and Z_{11} and Z_{22} are the self-surge impedance of each shield wire (1 and 2 are the shield wires, and n is the phase conductor) [1].

2.4.3 Computation of tower top voltage

The traveling wave solution for tower top voltage, V_T is derived by (2.17)

$$V_T(t) = Z_I\, I(t) - Z_W \sum_{n=1}^{N} [I(t - 2n\tau_T)\varphi^{n-1}] \tag{2.17}$$

where $V_T(t)$ is tower top voltage in (kV), t is time in (µs), $I(t)$ is stroke current into the equivalent circuit in (kA), Z_I is intrinsic circuit impedance in (Ω) faced by the current stroke at the time of entering the equivalent circuit, Z_w is a constant wave impedance. N in (2.17) is the largest value that the wave number, n can reach the largest whole number $\leq t/2\tau_T$.

$$Z_W = \left[\frac{2Z_S^2 Z_t}{(Z_S+2Z_t)^2}\right]\left[\frac{Z_t - R}{Z_t + R}\right] \tag{2.18}$$

τ_T is travel time in (µs) from tower top to base, $I(t - 2n\tau_T)$ is the stroke current that entered the equivalent circuit at a previous time $t - 2n\tau_T$, where n is a whole number, called the wave number, Z_S is the shield wire surge impedance (Ω), Z_t is the tower surge impedance (Ω), R is tower-footing resistance, φ is a damping constant that successively reduces the contribution of reflections;

$$\varphi = \left(\frac{2Z_t - Z_S}{2Z_t - Z_S}\right)\left(\frac{Z_t - R}{Z_t + R}\right) \tag{2.19}$$

2.4.4 Computation of cross arm voltages

The interpolated voltage for any cross arm, n is;

$$V_{pn}(t + \tau_{pn}) = V_R\,(t + \tau_T) + \frac{h_t - Y_n}{h_t}\,[V_T(t) - V_R\,(t + \tau_T)] \tag{2.20}$$

where h_t is the tower height (m) and Y_n is the distance from the tower top down to cross arm (m) [1].

2.4.5 Computation of insulator surge voltages

The insulator string surge voltage is the difference between the cross arm voltage (V_{pn}) and the voltage coupled to the phase conductor from the tower top [1];

$$V_{SN}\,(t + \tau_{pn}) = V_{pn}(t + \tau_{pn}) - K_n\,V_T\,(t + \tau_{pn}) \tag{2.21}$$

where K_n is the coupling factor and τ_{pn} is the time from tower top to cross arm. Combining the Equation yields;

$$V_{SN}\,(t + \tau_{pn}) = V_R(t + \tau_T) + \frac{\tau_T - \tau_{pn}}{\tau_T}\,[V_T(t) - V_R(t + \tau_T) - K_n\,V_T\,(t)$$

(2.21a)

2.4.6 Comparison of insulator voltage with voltage-time curve

To this point, all lightning voltage calculation has been for a unit current, namely kV of voltage per 1 kA stroke current entering the tower. The stroke current required to cause flashover must be determined from the calculated voltage waveform and the insulator volt-time curve or the air-gap voltage – time curve.

The surge voltage level at which an insulator or air gap will flashover is not a constant but it is a function of time to the flashover. The shorter the time to flashover, the greater the voltage. Figure 2.5 shows a mathematically convenient set of insulator volt-time curve published by Darveniza and other [9]. The upper left portion, for long insulator string and short times, is primarily an extrapolation because very few data are available. As a first approximation, the air-gap is less than the length of the insulator [1,9].

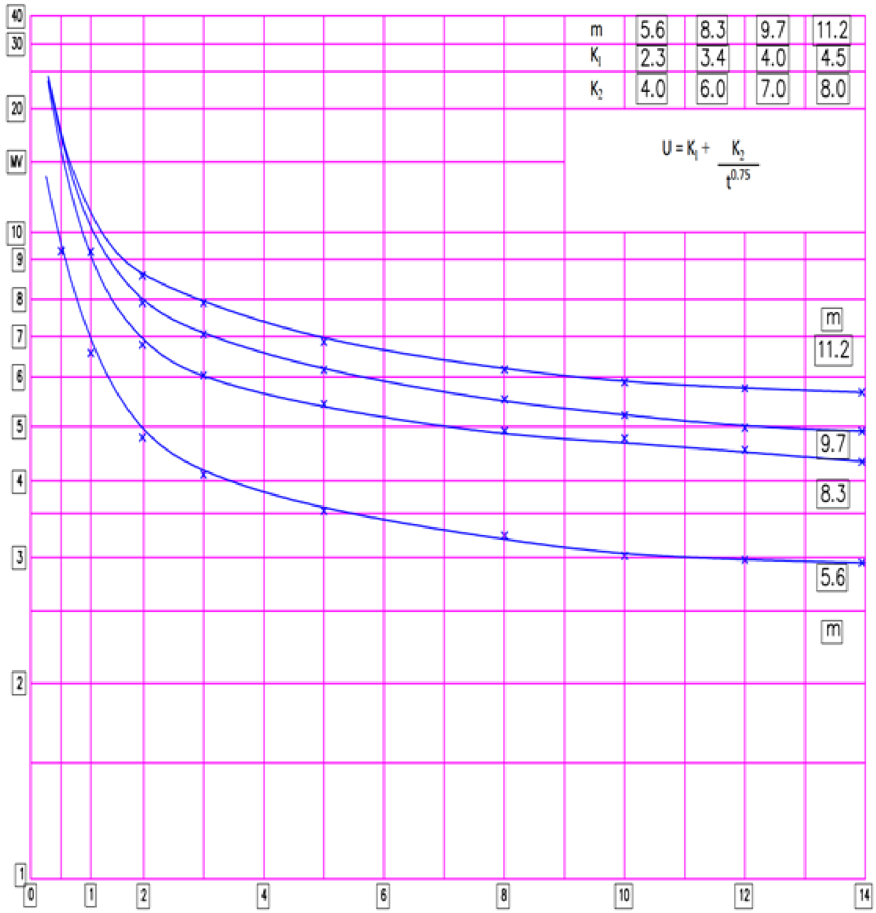


Fig. 2.5 Volt-time insulator flashover curves used for all calculation [9].

2.4.7 Reflection from adjacent towers

Reflection from adjacent towers can drive down the insulator voltages at the stricken tower by the reflected current waves. Depending on the span length, these reflections may arrive before or after the crest voltage that would otherwise occur at the stricken tower. The magnitude of the reflected voltage not readily determined by simple analytical means because the reflected waves are severely distorted by corona and resistance losses, which are functions of voltage rise time and distance [1].

The reflected voltage arriving at the tower top at crest time, t_0 is approximately equal in magnitude (but not dimensionally) to [1];

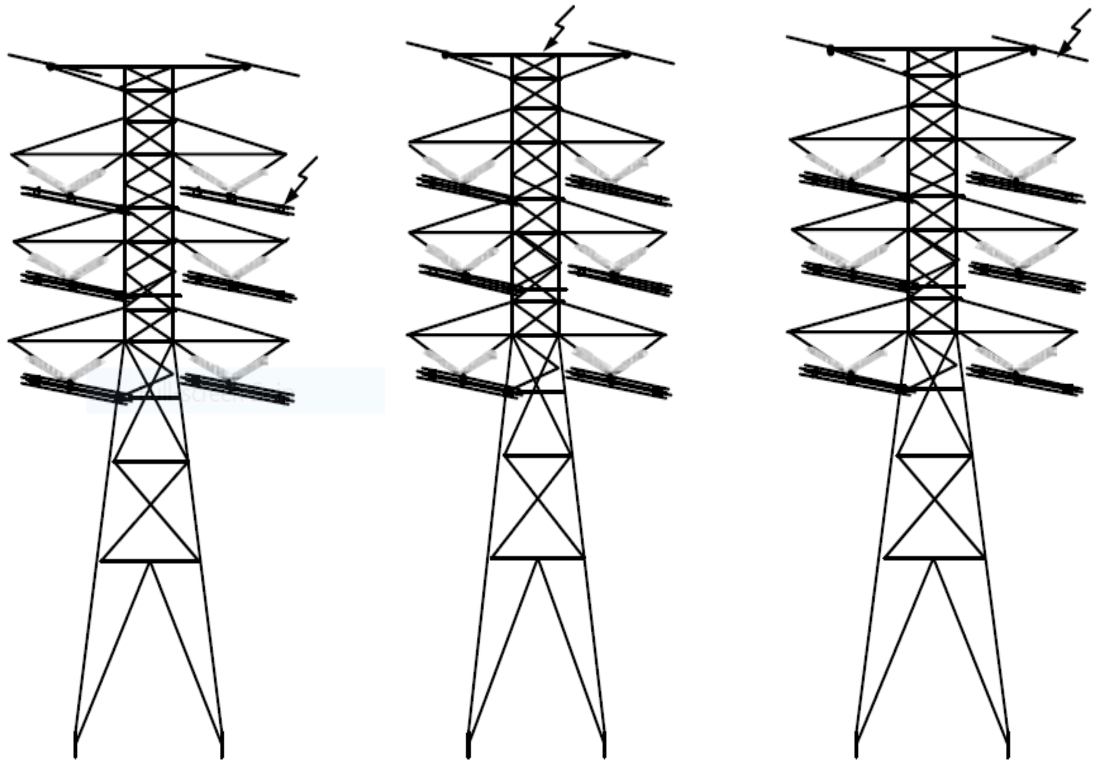
$$V_t'\ (t_0) = \frac{-4\ K_S[V_T(t_0)]^2}{Z_S}\left[1 - \frac{2V_T(t_0)}{Z_S}\right]\left[\frac{t_0 - 2\tau_S}{t_0}\right] \qquad (2.22)$$

where $V_t'\ (t_0)$ is sum of the reflected voltage waves from adjacent towers appearing at the tower top at crest time, t_0, $V_T(t_0)$ is crest tower top voltage at time t_0, without reflection from adjacent tower, $2\tau_s$ is 2-way travel time for a wave to and from the adjacent tower (μs) (twice the span distance in meter)/(300 x 0.9), Z_S is shield wire surge impedance (Ω). If;

$$V_t'(\ t_0) = 0\ (t_0 < 2\tau_s) \qquad (2.22a)$$

2.5 Direct lightning strokes to overhead power transmission lines.

When a direct lightning stroke occurs, the lightning current of large amplitude will be injected into the transmission line. Lightning can strike on transmission lines in many ways [11,19,20,21];



(a) (b) (c)

Fig. 2.6 Direct strokes on overhead lines

(a) Lightning stroke to phase conductor

(b) Lightning stroke to tower

(c) Lightning stroke to ground wire

2.5.1 Shielding Failure

Figure 2.6.(a) describe a shielding failure process, whre lightning strike to a phase conductor of a two-circuit transmission line. When the lightning hits a phase conductor with ground wire installed above the phase conductors, this phenomenon is called shielding failure [1,20,21].

2.5.2 Back-flashover

The back-flashover process is illustrated in Figure 2.6 (b) and (c). The lightning strike to the top of an overhead power transmission line or a ground wire near the tower top. The combination of the shield wire surge impedance and the injected lightning impulse current will produce a voltage at the tower top. In this case, lightning surge currents flow in the ground wire in both directions, and another surge propagates down the tower itself. If this lightning surge voltage generated at the tower is higher than the withstand voltage between the arcing horns, a flashover occurs and potentially results in a ground fault. This phenomenon is called back-flashover [11-27].

Lightning surge voltage due to shielding failure and back-flashover is of primary importance in assessing the lightning performance transmission and distribution lines and in developing the optimal design of the line. Thus, it is important to analyze the lightning surge on transmission and distribution lines with sufficient accuracy [21].

2.6 Arcing horn

Arcing horns are used to protect insulators on high voltage electric power transmission systems from damage during flashover. Horns are normally paired on either side of the insulator, one connected to the high voltage part and the other to the ground. They are frequently seen on insulator strings on overhead lines, or transformer bushings [28].

Arcing horns function by passing the high voltage across the insulator by means of aerial discharge. The small gap between the horns ensures that the air between them breaks down and conducts the voltage surge without damage to the insulator [28].

Fig. 2.7 Example of arcing horns

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3

Investigation Results

3.1 Overview

In this chapter, the data investigation results on the transmission line under study are presented as well as the effect of parameters on the number of lightning trip-out on the transmission line.

3.2 Transmission line under study

3.2.1 Line configuration

Figure 3.1 shows a plan of a 150-kV overhead transmission line between Payakumbuh - Koto Panjang under study, shown in the middle, with the total length of 86 km. The studied line is a double-circuit, balanced-insulation and transposed transmission line. The IKL was as many as 165 days/ year in the area where the line segment between No. 1 to No. 140 towers, 47 km in length, locates, while the IKL was 22 days/ year in the area where the line segment from No. 141 to No. 248 towers locates.

Figure 3.2 shows the typical configuration of towers. The towers consist of four types, namely A, B, C and D types depending on the crossing angle. Table 3.1 shows the dimension, the component ratio and the frequency ratio of the lightning trip-outs dependent on tower types. The four types of towers had almost the same dimensions [1,2]. The types of towers might be chosen dependent on the easiness of the construction. The range of the span length was from 147 m to 434 m with an average of 333 m.

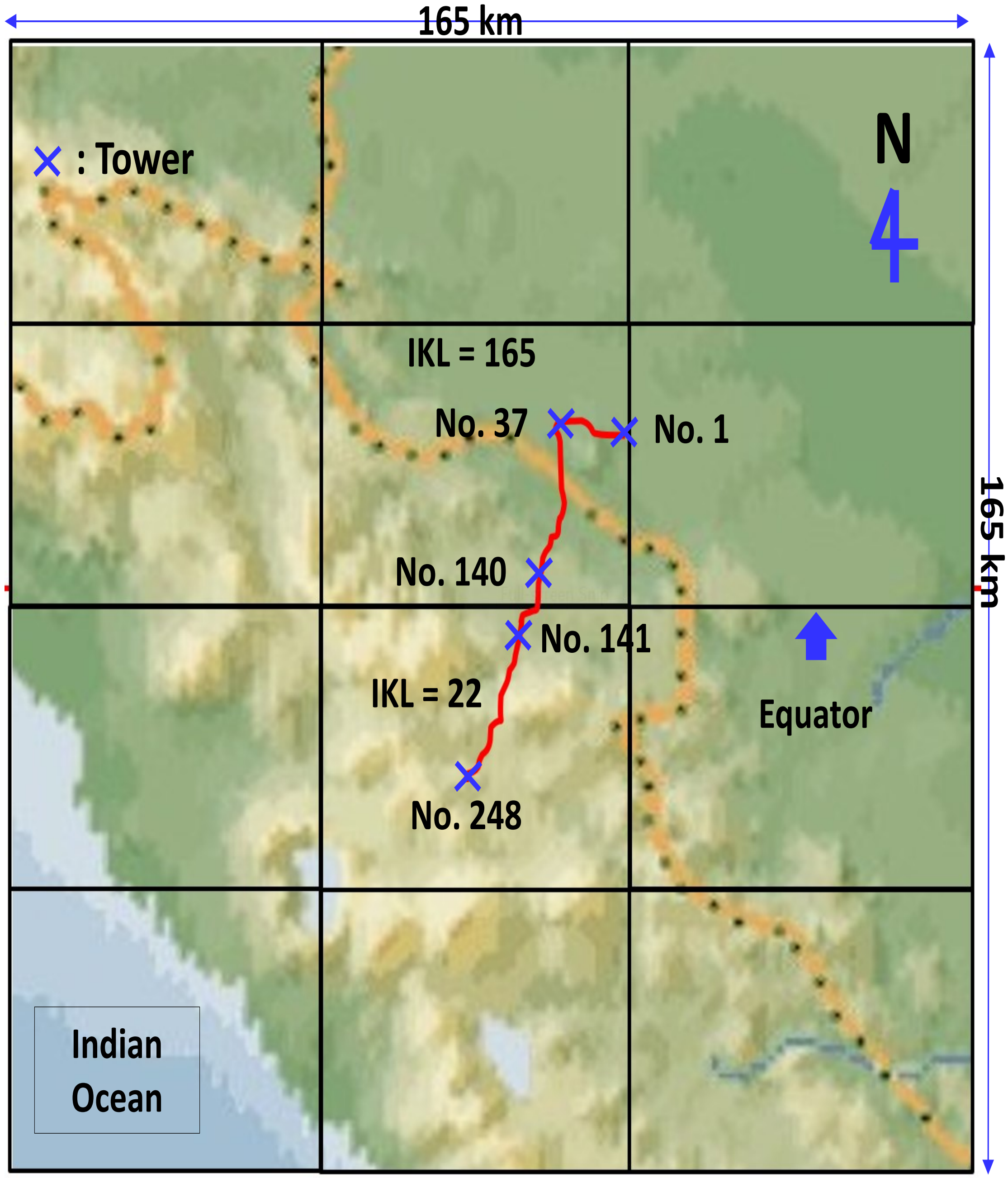

Fig. 3.1. Map of Isokeraunic Level of West Sumatra and Location of Transmission line [1,2].

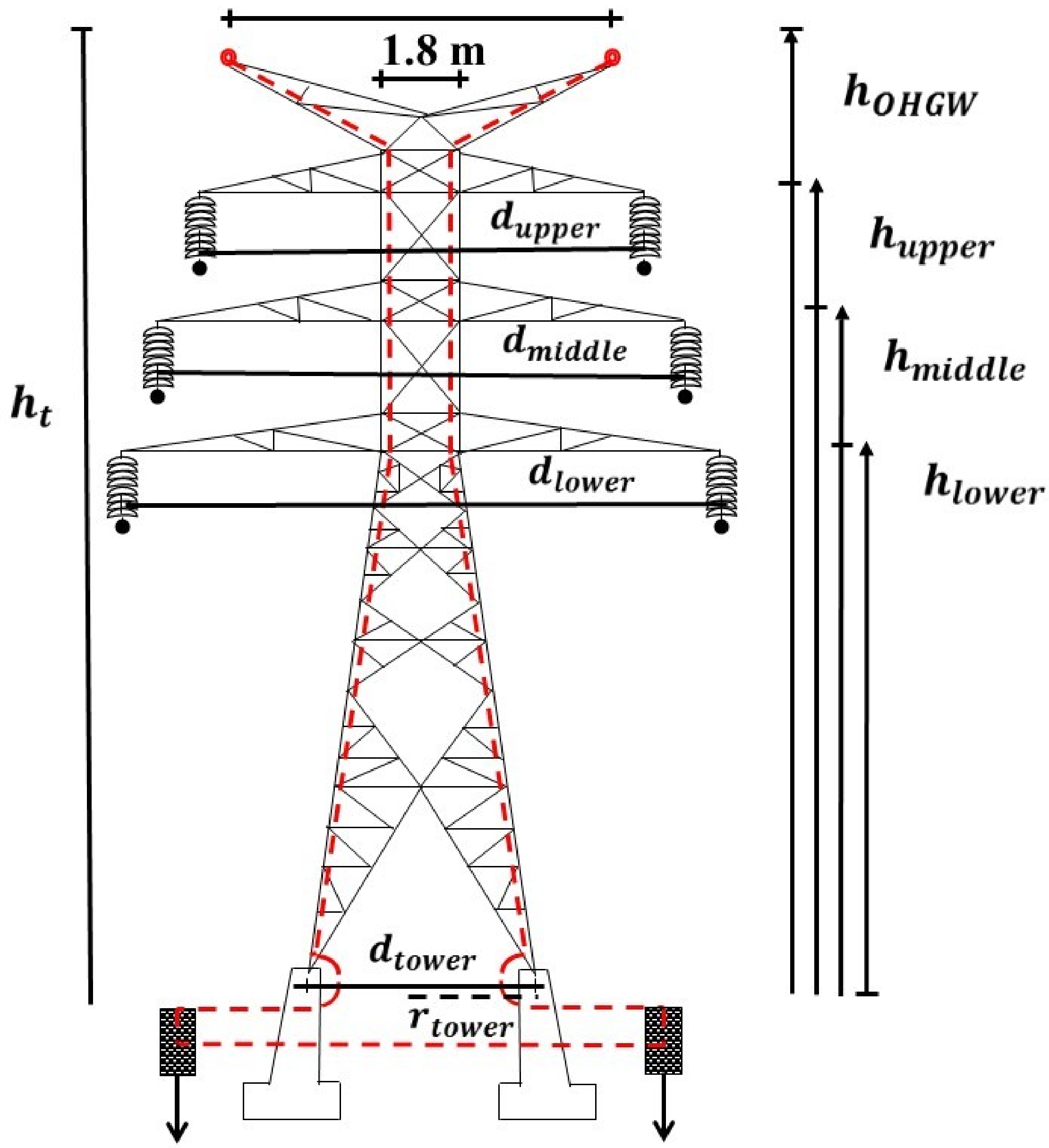

Figure 3.2. Configuration of towers [1,2,3].

Table 3.1. Dimension, component ratio, and frequency of lightning trip-out dependent on tower types [2,3].

	Tower Types			
	A	B	C	D
d_{OHGW}	7.0	6.8	6.8	7.0
d_{Upper}	7.6	7.0	7.0	7.6
d_{Middle}	8.0	7.4	7.4	7.6
d_{Lower}	8.45	7.8	7.8	7.6
d_{Tower}	5.0	5.4	5.4	5.6
h_{OHGW}	32.2	31.7	31.7	31.7
h_{Upper}	28.1	27.7	27.7	27.7
h_{Middle}	23.8	23.6	23.6	23.6
h_{Lower}	19.5	19.5	19.5	19.5
Crossing angle of line	0° - 3°	0° - 20°	20° - 40°	40° - 60°
Component ratio (%)	53.6	28.6	10.7	7.1
Frequency ratio of tripout (%)	60.5	30.2	8.1	1.2

Table 3.2 shows the line condition. The line had two galvanized overhead ground wires (OHGW), 9.6 mm in diameter, and the sag was 1.5% of the span length of the towers.

Table 3.2. Line condition

OHGW	Line Type	Ground Steel Wire (GSW)
	Diameter	9.6 mm
	Sag	1.5% of span length
Phase conductor	Line type	ACSR Aluminum Conductor Steel Reinforced)
	Diameter	25.5 mm
	Sag	2% of span length
Insulator	Type	11 porcelain suspension insulators
	BIL	1.21 – 1.27 MV
	Diameter	254 mm
	Total length	1.6 – 1.87 m
Arching horn	Length of an arcing horn gap	0.9 – 1.6 m
TLA	Location	10 towers (4 to 6 pieces)
Span length	147 m – 434 m (average 333m)	

Each phase conductor was the ACSR (Aluminum Conductor Steel Reinforced), 25.5 mm in diameter, and the sag was 2% of the span length. The string of 11 porcelain suspension insulators, 254 mm in diameter and 1.6 to 1.87 m in total length, had the BIL (Basic Insulation Level) of 1.21 – 1.27 MV. In addition to the OHGW, transmission towers had other lightning protection systems such as arcing horns and TLAs (Transmission Line Arrester).

Figure 3.3 shows the distribution of the length of an arcing horn gap installed at each tower [2].

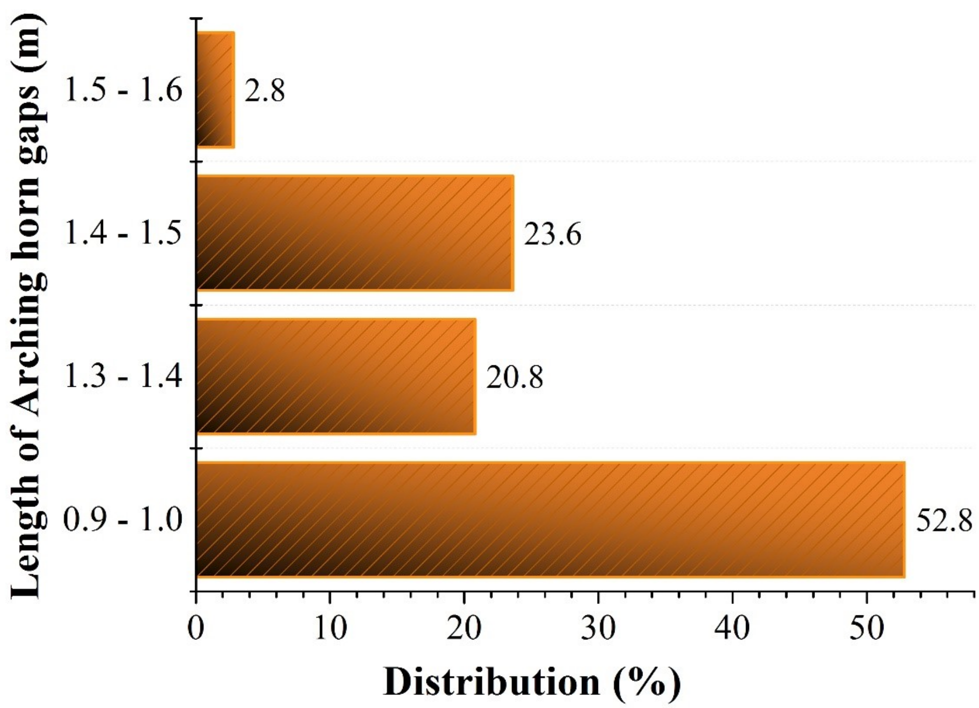

Fig. 3.3. Distribution of the length of an arcing horn gap from No. 1 to No. 140 towers [2].

The arcing horn gap is arranged 75% to 85% of the length of the insulator string, 1.2 m to 1.6 m. At the towers with frequent insulator damages, the length of an arcing horn gap is shortened to 0.9 – 1.0 m, and as a result, more than half of the horns had the length from 0.9 m to 1.0 m. The 4 to 6 pieces of the TLAs were installed at 10 towers among No.1 to No.140 towers dependent on the frequency of the flashovers [2].

3.2.2 Tower-footing resistance

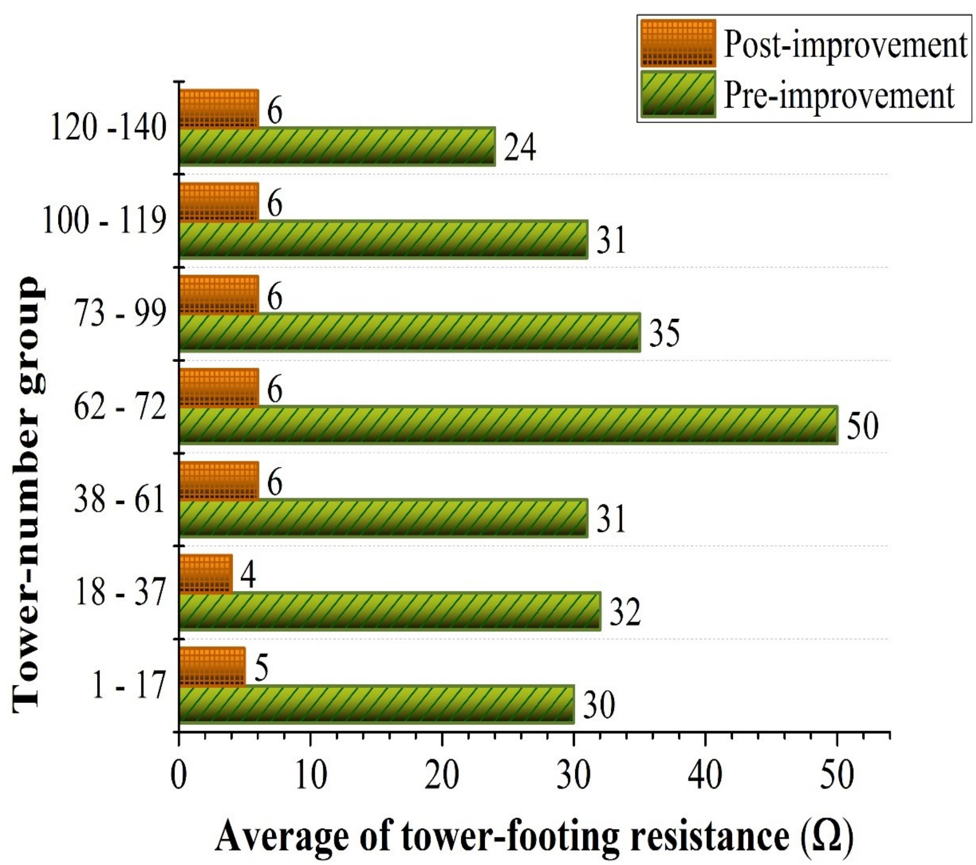

Fig. 3.4. Measurement data of average value of tower-footing resistance at No. 1 to No 140 towers.

Figure 3.4 shows the average tower-footing resistance as a function of the tower-number group before and after the improvement of the tower-footing resistance, carried out from 2010 to 2014.

The average tower-footing resistance for the tower-number group before and after the improvement was in the ranges from 24 to 50 Ω and from 4 to 6 Ω, respectively. The average periods of observation before and after the improvement of tower-footing resistance are shown in Table 3.3. The average periods before and after the improvement were 3.3 and 1.8 years, respectively.

Table 3.3. Average periods of observation before and after improvement of tower-footing resistance.

Tower group	Average period	
	Pre-improvement	Post-improvement
1 - 17	3.3	1.7
18 - 37	3.1	2.0
38 - 61	3.2	2.0
62 - 72	3.4	1.6
73 - 99	3.5	1.5
100 - 119	3.2	1.8
120 - 140	3.3	1.8
Average	**3.3**	**1.8**

3.3 Factor influencing lightning trip-outs

The number of towers experiencing flashover resulting in lightning trip-outs before and after the improvement of tower-footing resistance was 38 and 8, respectively. The location of flashover is identified by a fault locator. The lightning trip-out rates of the line segment between No. 1 to No. 140 towers before and after the improvement of the tower-footing resistance were 114 and 22 flashover /100 km-year, respectively. Therefore, it is confirmed that the improvements of tower-footing resistance resulted in the reduction of a number of lightning trip-outs. According to [4] the average lightning trip-out rates of 110 kV to 154 kV lines from 1980 to 2000 was 3.25 flashover/ 100 km-year in Japan where the average IKL was from 20 to 30. In Japan, the length of an arcing horn gap of the 154 kV transmission line is often arranged 1.2 m [5]. The high trip-out rate in Indonesia even after the improvement of the tower-footing resistance might be due to the high IKL and the short the length of an arcing horn gap shown in Fig. 3.3.

3.3.1 Lightning activity

Figure 3.5 shows the trip-out rate as a function of the line segment expressed by the tower-number group. The rate decreases with the increase of the tower number with which the location of towers first directs toward the east and then to the south. In the area of the line, the lightning activity is high in the north and weakens in the south as is indicated by the decrease of the IKL from 165 to 22 days/ year. The lightning activity might be the cause of the decrease of the rate of the line segment with the increase of the tower number.

Since the trip-out rates of the line segment between No. 73 – No. 140 towers are relatively low probably due to the low lightning flash density, the following analysis will be made for the line from No. 1 to No. 72 towers to clarify the degree of influence of some factors.

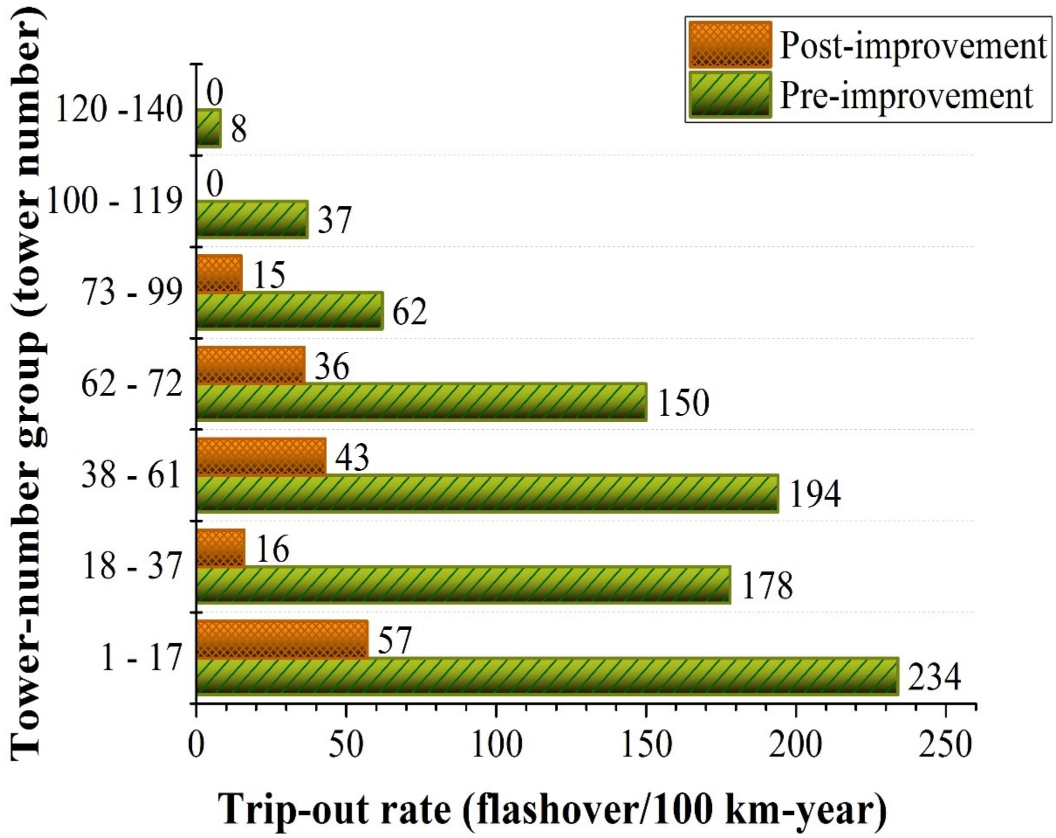

Fig. 3.5. Trip-outs rate as a function of the tower-number group.

3.3.2 Tower-footing resistance

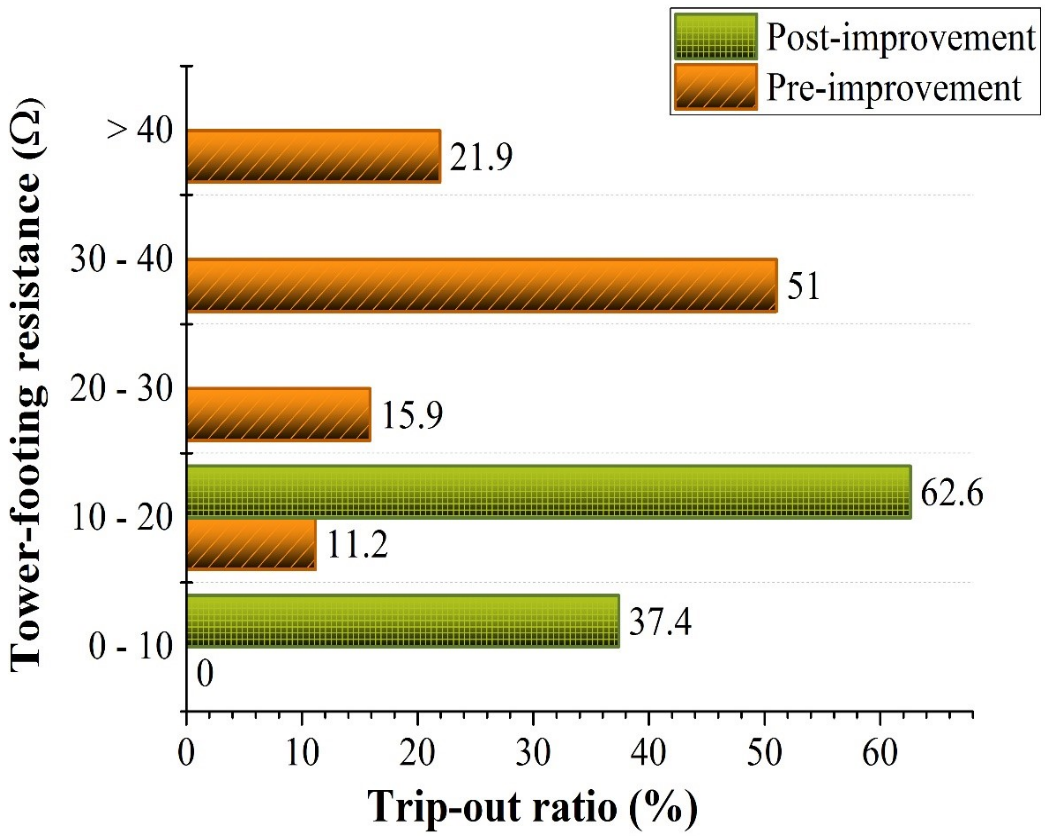

Fig. 3.6. Trip-out rate as a function of tower-footing resistance.

Figure 3.6 shows the trip-out ratio of the number of trip-outs for a tower for a year as a function of the tower-footing resistance. The number of towers in the tower-footing resistance segment was from 10 (10 – 20 Ω) to 32 (20 – 30 Ω) before the improvement, and that was 5 (10 – 20 Ω) and 67 (0 – 10 Ω) after the improvement. The trip-out ratio increases with the increase of the grounding resistance excluding the trip-out ratio of the segment for 30 – 40 Ω before the improvement of tower-footing resistance. Table 3.4 shows the parameters of towers with frequent lightning trip-outs and the grounding resistance of 8 towers out of 10 is in the range of 30 - 40 Ω. This is the reason for the high trip-out rate in the resistance segment of 30 - 40 Ω.

Table 3.4. Parameters of towers with frequent trip-outs before improvement of tower footing resistance

Tower No.	Grounding resistance (Ω)	Span length (m)	Altitude (m)	Tower top height difference (m)	Number of trip-outs
10	38	308	269	8.95	11
16	35	416	158	24.70	18
17	35	385	154	22.45	12
19	38	422	201	20.75	6
43	36	389	110	7.90	6
46	31	286	151	3.25	6
48	45	321	166	4.55	10
50	25	278	166	8.70	8
61	31	402	266	179	6
67	33	222	307	12.65	8

Before the improvement of tower-footing resistance, the highest trip-out rate was found at No. 16 tower with the tower-footing resistance of 35 Ω and the average tower-footing resistance at the towers experiencing lightning trip-outs was 48 Ω. After the improvement of the tower-footing resistance, the highest trip-out rate was found at No. 47 tower with the tower-footing resistance of 15 Ω and the average tower-footing resistance of the towers with lightning trip-outs, was 11 Ω.

3.3.3 Span length

Figure 3.7 shows the lightning trip-out ratio of the number of flashover for a tower for a year as a function of the span length.

The number of towers in the span length range was from 10 (150 – 250 m) to 32 (351 –450 m). It is reported that the trip-out ratio is high for towers with long span length because of the increase of the lightning flashes to the line [4-8]. The trend that the trip-out ratio becomes high with the increase of the span length is significant after the improvement of the tower-footing resistance. However, the trend is weak before the improvement of the tower-footing resistance. This is because in the case of the high tower-footing resistance the flashover occurs before the arrival of the wave reflected from the adjacent towers due to the high potential rise of the tower. Therefore, the degree of the influence of the span length on the trip-out ratio is dependent on the tower-footing resistance.

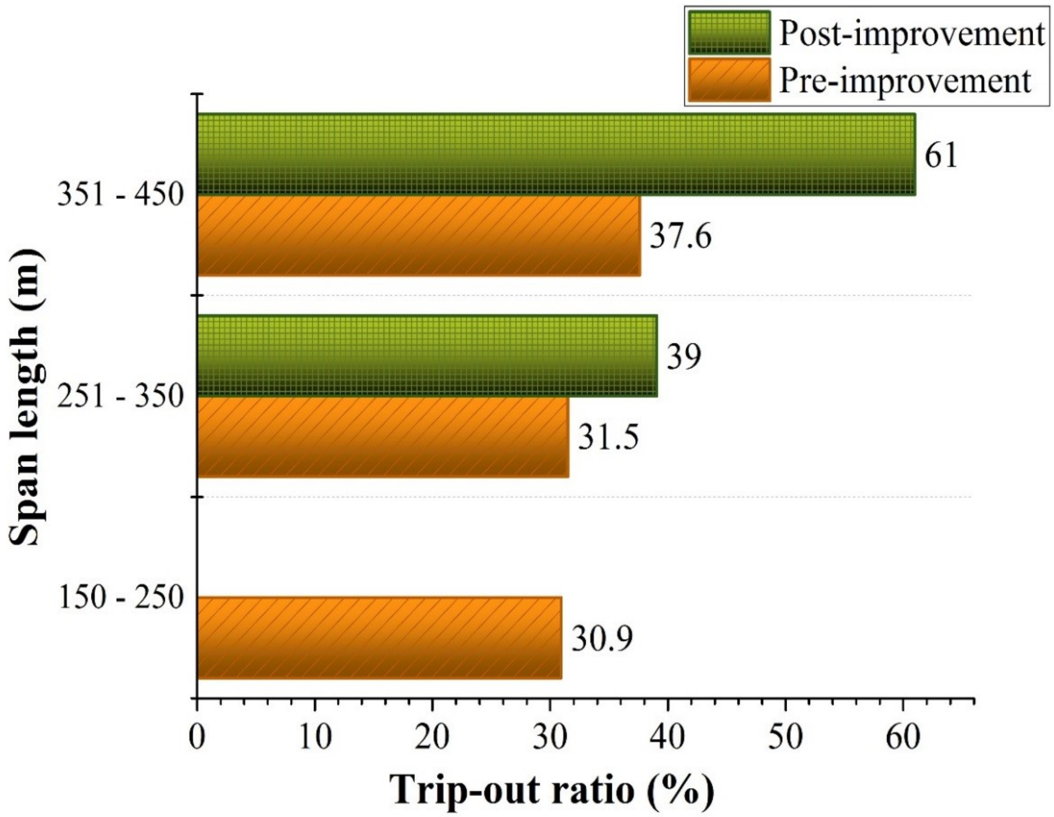

Fig. 3.7. Trip-outs rate as a function of the span length.

3.3.4 Altitude of towers

Figure 3.8 shows the trip-out ratio as a function of the altitude of the towers. The number of towers in the altitude range was from 6 (301 –400 m) to 43 (100 – 200 m). It is reported that with the increase of the altitude, the trip-out ratio increases [4-8]. However, such a trend cannot be seen in Fig. 3.8 because the altitude of 6 towers out of 10 in Table 3.3 is in the range of 100 - 200 m. The degree of the influence of the altitude of the tower is not significant on the transmission line under study.

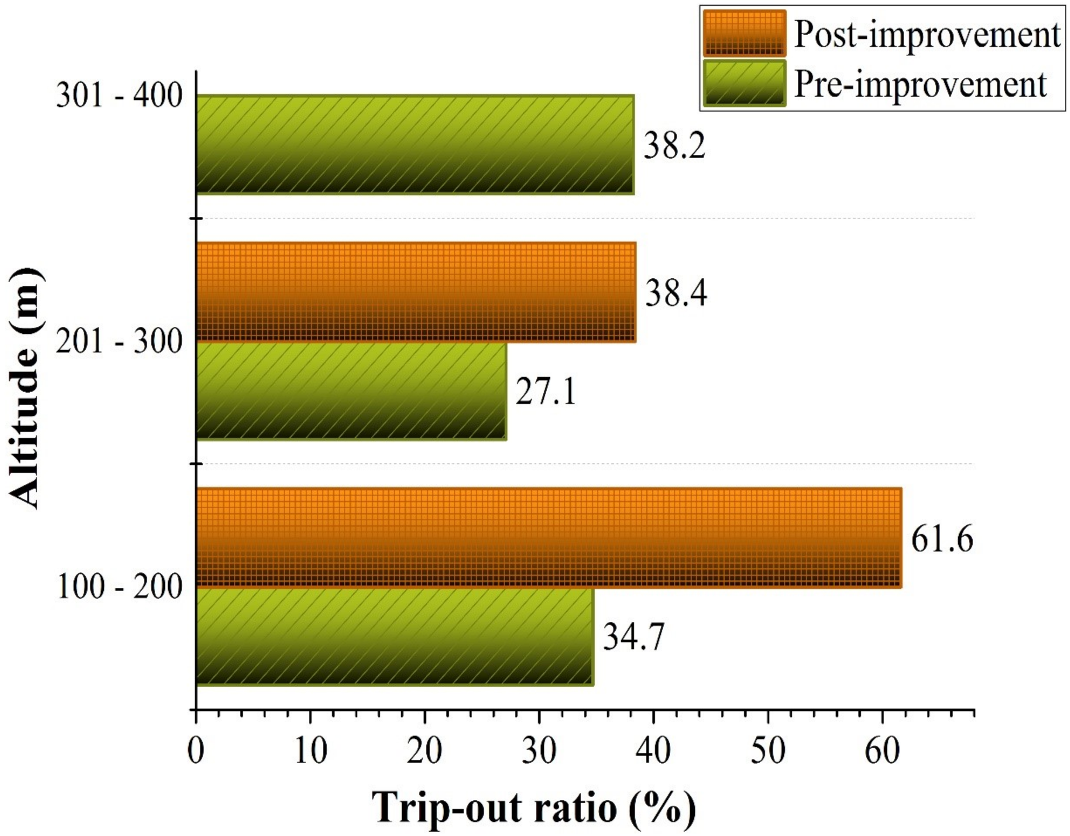

Fig. 3.8. Trip-outs rate before and after improvement as a function of the altitude.

3.3.5 Height difference of tower tops

Figure 3.9 shows the trip-out ratio as a function of the height difference of the tower top.

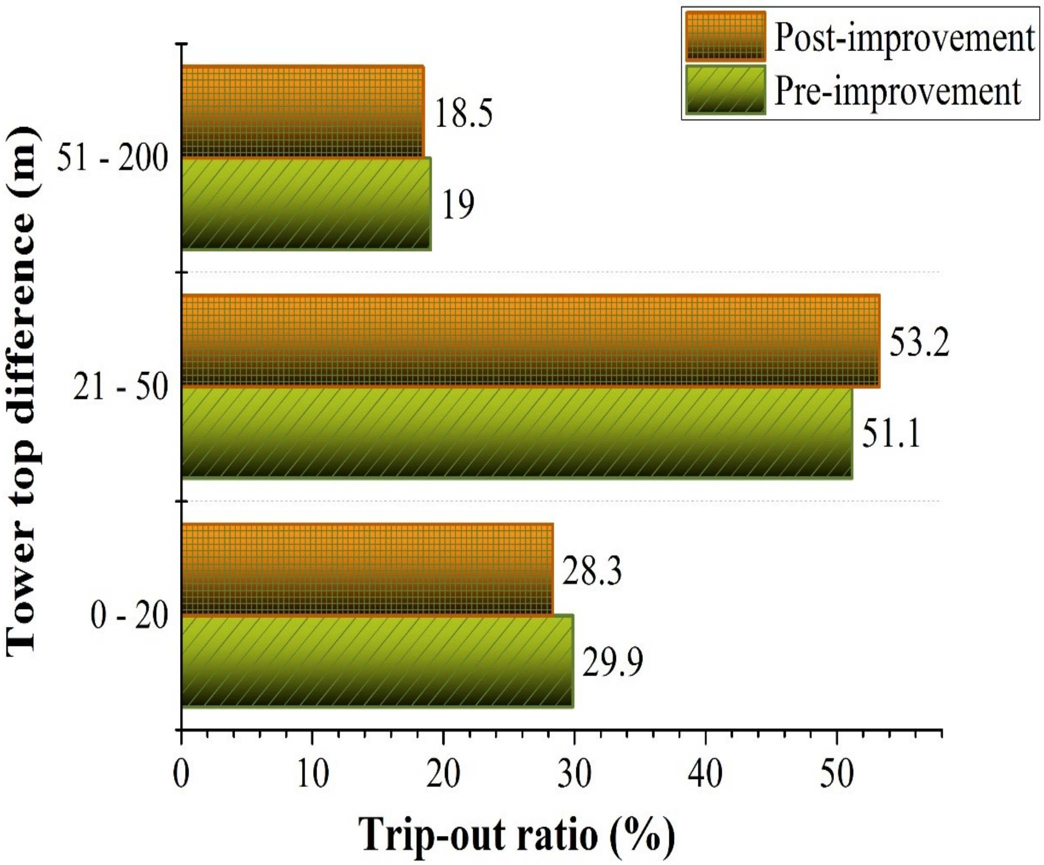

Fig. 3.9. Effect of tower-height difference on the trip-out ratio.

The height difference of tower tops is calculated as the average difference of the absolute value of the tower top from two adjacent towers. The number of towers in the tower top difference range was from 13 (21 – 50 m) to 44 (0 – 20 m). It is reported that the larger of the difference of the tower-top height, the higher the trip-out ratio [4-8]. However, in our dataset, there seems almost no relation because the difference of the 44 towers out of 72 is in the range of less than 20 m with 83 trip-outs out of 143. The result of investigation shows that the difference of the tower top is not a dominant factor on the transmission line under study.

3.3.6 Length of an arcing horn gap

The trip-out ratio before and after the improvement of the tower-footing resistance is shown as a function of the length of an arcing horn gap in Fig. 3.10.

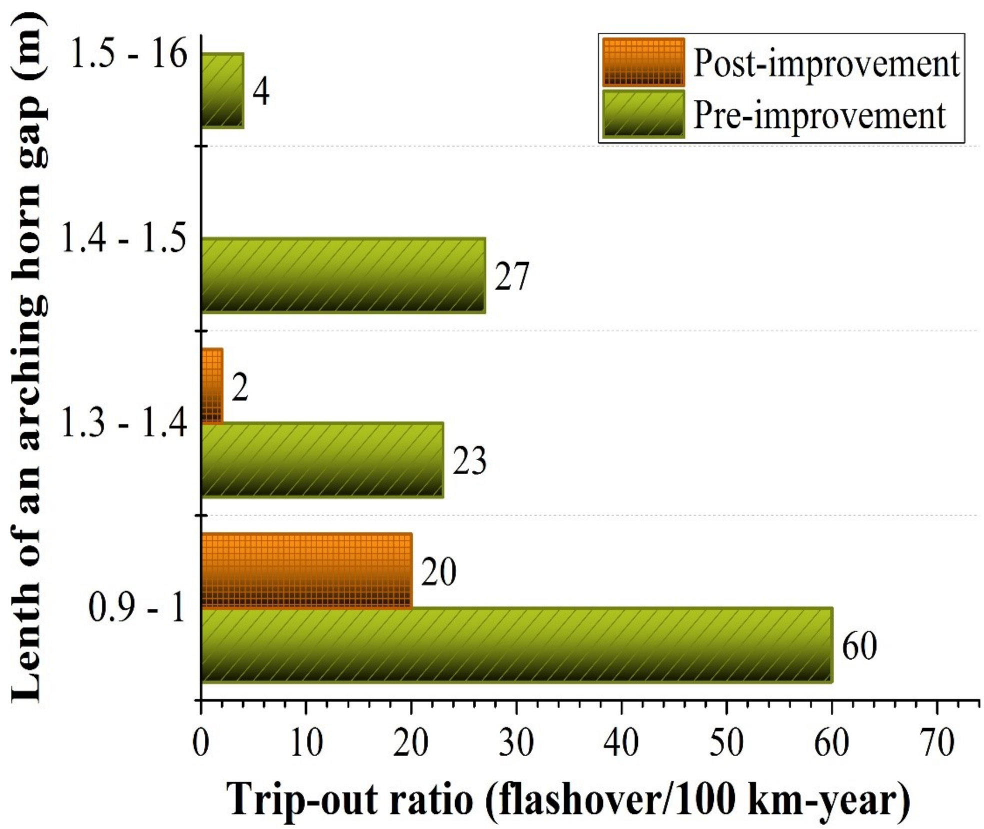

Fig. 3.10. Trip-out rate as a function of length of an arching horn gap.

The frequency of trip-outs at the towers with the length of an arcing horn gap range of 0.9 – 1.0 m is much higher than the tower with the length of an arcing horn gap of longer than 1.3 m after the improvement of the tower-footing resistance. This is because the flashover voltage decreases with the decrease of the length of an arcing horn gap. The length of an arcing horn gap of 9 towers in Table 3.3 was 0.9 m and the length of an arcing horn gap of the No. 46 tower was 1.3 m. Note that the trip-pout ratio at the towers with the length of an arcing horn gap of 0.9 – 1.0 m, defined as the number of the flashovers for a tower for a year, was 44.6 % before the improvement, however, the ratio of the total number of flashovers was 70 % and 90% before and after the improvement, respectively.

3.4 Location of flashover

Figure 3.11 shows the trip-out rate in circuits I and II of the line between No. 1 and No. 140 towers. The high rate of lightning trip-outs before and after the improvement of the tower-footing resistance is seen in circuit I. This is due to the placement of circuit I on the north side from No. 1 to 37 towers, and on the east side from No. 38 to No. 140 towers. In this area, the thunderstorm often approaches the line from the northeast and the towers often located on the ridge of the mountain. Therefore, the insulator voltage on the circuit I is high due to the topology.

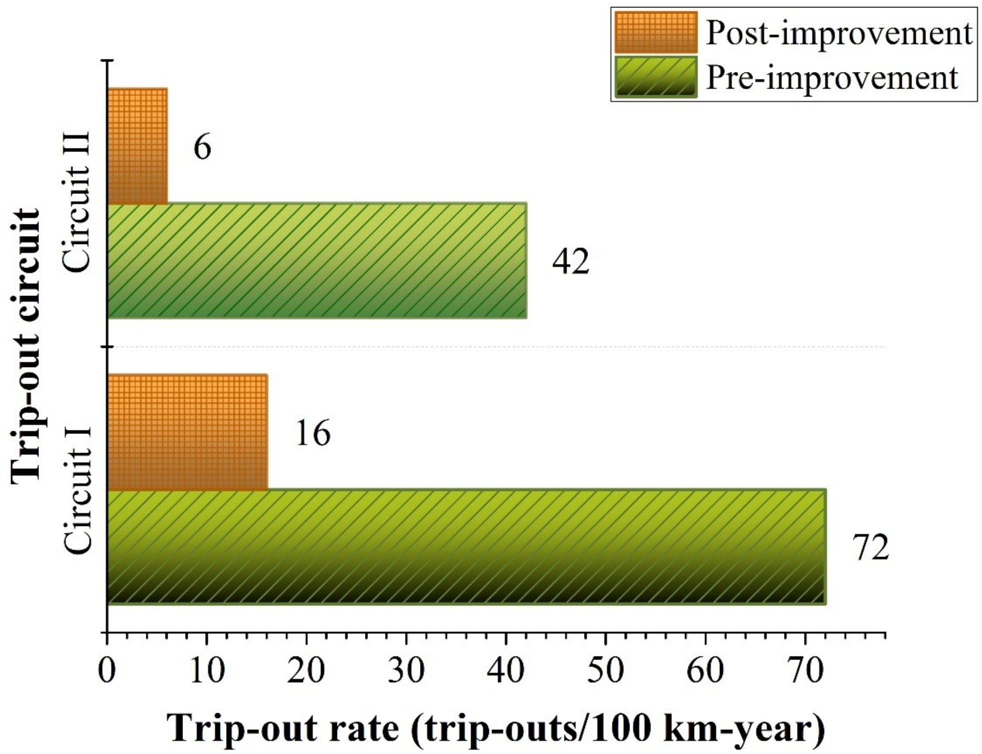

Fig. 3.11. Rate of trip-outs for circuits I and II

Figure 3.12 shows the trip-out rate as a function of the location of flashover. The high rate of lightning trip-outs before the improvement of the tower-footing resistance arises at the lower arm. After the improvement of tower-footing resistance, the high trip-out rate occurs at the upper arm. Since the location of the trip-out is not influenced by the tower-footing resistance and depends on the struck phase in case of shielding failure, the main cause of the flashover is inferred to be the back-flashover.

The insulator voltage is given by (3.1) as the difference of the voltage of the phase wire and the voltage at the arm. The voltage at the phase wire is induced due to the coupling of the OHGW and the phase conductor. Therefore, the voltage is dependent on the current on the OHGW, while the arm voltage is dependent on the current flowing through the tower into the ground. When the tower-footing resistance is so small that the current flowing through the tower plays a dominant role on the insulator voltage, the insulator voltage at the upper arm is high at the wave front of the lightning current waveform due to the delayed arrival of the reflected wave at the interface of the tower and the ground. With the increase of the tower-footing resistance, the current on the OHGW increases and the role of the phase conductor voltage increases in the determination of the insulator voltage. In this case, due to the geometry, the insulator voltage at the upper arm becomes low compared with the insulator voltage at the lower arm. Therefore, the trip-out rates at the line on the lower arm become higher [10,11]

$$V_{insulator} = V_{phase}\text{-}V_{arm} \tag{3.1}$$

where $V_{insulator}$ is the insulator voltage (V), V_{phaset} is the phase conductor voltage due to coupling of the the OHGW and phase conductor (V), V_{arm} is the arm voltage (V).

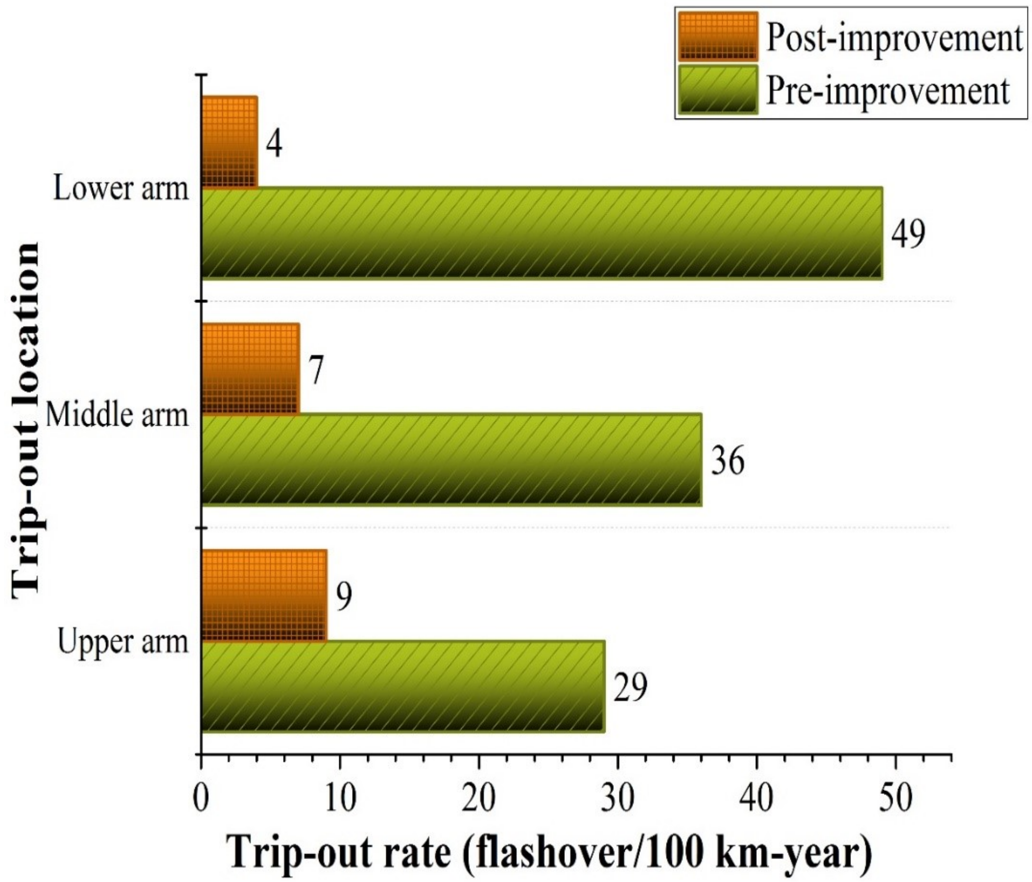

Fig. 3.12. Rate of trip-outs as function of flashover location

Location of No. 1 to No. 140 towers based on actual data are shown in Figure 3.13a.

Fig. 3.13.a. Location of No. 1 to No. 17 towers [12].

Fig. 3.13.b. Location of No. 18 to No. 37 towers [12].

Fig. 3.13.c. Location of No. 38 to No. 61 towers [12].

Fig. 3.13.d. Location of No. 62 to No. 72 towers [12].

Fig. 3.13.e. Location of No. 73 to No. 99 towers [12].

Fig. 3.13.f. Location of No. 100 to No. 119 towers [12].

Fig. 3.13.g. Location of No. 120 to No. 140 towers [12].

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4

Analysis

4.1 Overview

In this thesis, we present a simplified two-point method and IEEE Flash program for computing lightning trip-out rates of transmission lines. This chapter explains a calculation method and a numerical example for double circuit tower.

4.2 Line model and lightning incidence to transmission line

A 47 km–long double-circuit line with the span length of 333 m, simulating the line from No. 1 to No. 140 towers, was selected to estimate the lightning performance of the transmission line under study. As the most of the flashovers occur at the length of an arcing horn gap of 0.9 m, the length of an arcing horn gap is assumed to be 0.9 m.

The ground flash density is calculated by (2.2) [1-5] by assuming the thunderstorm day is equal to the IKL of 165 days-year. In this way, the ground flash density is calculated to be 23.65 flashes/km^2-year.

Lightning incidence to overhead lines was calculated to be 548.4 flashes/100 km-year through (2.3) [1-2].

The cumulative frequency distribution of the lightning current is assumed to be given by (2.4) [1-2].

The back-flashover rate, BFR, is given as the product of this probability and the number of strokes that terminate on the towers. For simplicity, the number of strokes to the towers is assumed to be 60% of all strokes to the line as in (6) [1-2].

$$\mathrm{BFR} = 0.6\ \mathrm{N_S}\ \mathrm{P(I_C)} \quad (4.1)$$

where I_C is the critical current resulting in back-flashover.

4.3 Method of calculation of critical current

The critical current resulting in the flashover is evaluated at two times, namely 2 μs and 6μs, as in the case of the IEEE FLASH program by assuming the front duration of the lightning current 2 μs. Such a simplified method is used because the objective of this thesis is to Timprove the lightning protection design of the transmission line. In the method, the insulator voltage is calculated by the difference between the phase voltage and the arm voltage as in [1]. The voltage and current are calculated by the distributed constant circuit theory by taking account of the coupling between the OHGW and the phase conductors, the reflection at two adjacent towers and the reflection at the interface of the struck tower and the ground.

The corona-coupling model is incorporated through the approximate diameter of the corona sheath [1]. The ionizing effect of the ground is taken into account [2,7] through very simple method (four parallel, in Figure 4.1) and the power-frequency voltage is also taken into account.

The critical flashover voltage (CFO) is calculated based on the time to flashover by (4.2) [1,2,3,4,8,9].

$$\mathrm{CFO} = \left(400 + \frac{710}{t^{0.75}}\right)\ \mathrm{D} \quad (4.2)$$

where CFO is critical flashover voltage, t is time to flashover and D is the gap or insulator length (m).

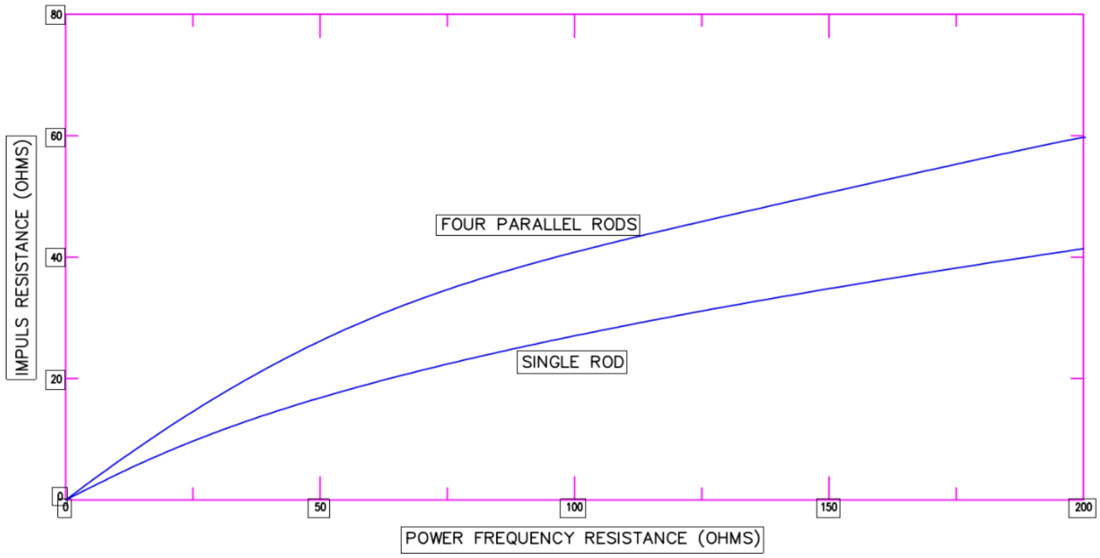

Fig. 4.1. Impulse current resistance of concentrated ground derived from laboratory test data [1,7].

4.4 Method of analysis

The authors estimated the lightning trip-out rate by the IEEE FLASH program, primarily developed based on the method in [1,2,9]. In this thesis, the trip-out rate is also estimated by the IEEE method [1,2,9] to study the dependence of a trip-out rate on the location of flashovered phase conductors, not provided by the IEEE FLASH program.

Please refer to [1] for the detail of the method of analysis. The followings are the brief summary of the method.

(1) The voltage and current are calculated by the distributed constant circuit theory by taking the coupling between the OHGW and the phase conductors into account.

(2) The reflection of traveling waves at two adjacent towers and the reflection at the interface of the towers and the ground are taken into account.

(3) The corona-coupling model is incorporated into the approximate diameter of the corona sheath [1].

(4) The ionizing effect of the ground is taken into account [1] through very simple method and the power-frequency voltage is also taken into account.

Such a simplified method is used because the objective of this thesis is to investigate the reproducibility of the observed characteristics of the trip-out rate.

4.4.1 Line Model and Lightning Incidence to Transmission Line

A 47 km – long double-circuit line with the span length of 333 m, simulating the line from No. 1 to No. 140 towers, was selected to estimate the lightning performance of the transmission line under study. The length of an arcing horn gap is assumed to be 0.9 m or 1.3 m.

The surge impedance of towers calculated by using (4.3)[1] is 174 Ω and is used in the analysis. Regardless of the tower types, value of surge impedance are almost the same as in Table 4.1.

Table 4.1. Surge impedances of the towers based on tower types

Surge impedances (Ω)	Tower types			
	A	B	C	D
	174	169	169	167

$$Z_t = 30 \ln \left[\frac{2\left(h_t^2 + (r_{Tower})^2\right)}{(r_{Tower})^2} \right] \quad (4.3)$$

where Z_t is the surge impedance of the tower (Ω), h_t is the tower height and r_{tower} is the tower base radius (m), respectively.

The ground flash density is calculated by (3) [1]. For the thunderstorm day of 165 days/year. The ground flash density is calculated to be 23.7 flashes/km^2-year.

$$N_g = 0.04 \; TD^{1.25} \quad (4.4)$$

where N_g is the ground flash density (flashes/km^2-year), TD is the thunderstorm days (days-year).

Lightning incidence to overhead lines was calculated to be 548 flashes/100 km-year through (4) [1].

$$N_s = \frac{N_g}{10}\left(28h_t^{0.6} + d_{OHGW}\right) \quad (4.5)$$

where N_s is the number of strokes to a line (flashes/100 km-year), h_t is tower heights (m), d_{OHGW} is overhead ground wire separation distance (m).

The cumulative frequency distribution of the lightning current is assumed to be given by (5) [1].

$$P(I) = \frac{1}{1+\left(\frac{I}{31}\right)^{2.6}} \tag{4.6}$$

where I is lightning current amplitude in units of kA, P is the probability of occurrence of lightning current amplitude higher than I.

For simplicity, the number of strokes to the lines resulting in flashover is assumed to be 60% of all the strokes to the line [1].

4.4.2 A simplified two-point method for computing lightning performance of transmission line

In this section, a calculating method is used, and a numerical example for double circuit tower is presented [1].

4.4.3 Basic of method

The method is based on the following concepts.

Most lightning trip-outs from back-flashovers are caused by strokes with magnitudes of 80 kA or higher (frequently much higher) and Figure 12.4.8 in [1] indicates that a stroke waveshape with time-to-crest in the 1.8 to 2.0 µs range or more would simulate field observations reasonably well.

Reflection from adjacent towers can reduce tower top potentials and significantly reduce the line flashover rate. The reflections are distorted by corona currents, and their velocity of propagation is showed appreciably by resistance and corona effects. The velocity of 0.9 c for waves from adjacent towers, where c is 300 m/μs, the velocity of light, although, in reality, different parts of these reflected waves travel with different velocities. Thus, if an adjacent tower is 300 m away, these slowed reflections would start arriving at the stricken tower at about 2.2 μs. Even for a 200 m span, about 1.5 μs will elapse before reflections start reducing the voltages at the stricken tower. Because most transmission spans average 200 m or more in length, one may simply select a stroke front time of 2 μs as a standard waveshape from Figure 12.4.8 in [1] and then correct for reflection from the nearest tower.

The volt-time curves are referred to only two points. Figure 4.2 shows the per-unit stroke current wave adopted as the standard and the two points. The lower of the two stroke currents is then used as the true critical stroke current for flashover calculations. Flashovers beyond 6 μs are assumed to be infrequent because of the flattening of the volt-time curve. The two voltages, A and B, are computed for each insulator on the tower unless it is determined by inspection that the insulators have identical stresses.

Subsequent strokes are ignored. The analysis suggests that as far as the severity of voltage across the insulators is concerned, subsequent strokes in the same flash are no worse than the first stroke, in the sense that subsequent stroke creates more insulator voltage but at shorter times where the insulator strength is higher.

By selecting the two points at time of 2 and 6 μs, all the voltage equation are greatly simplified with t_0 equal to 2 μs.

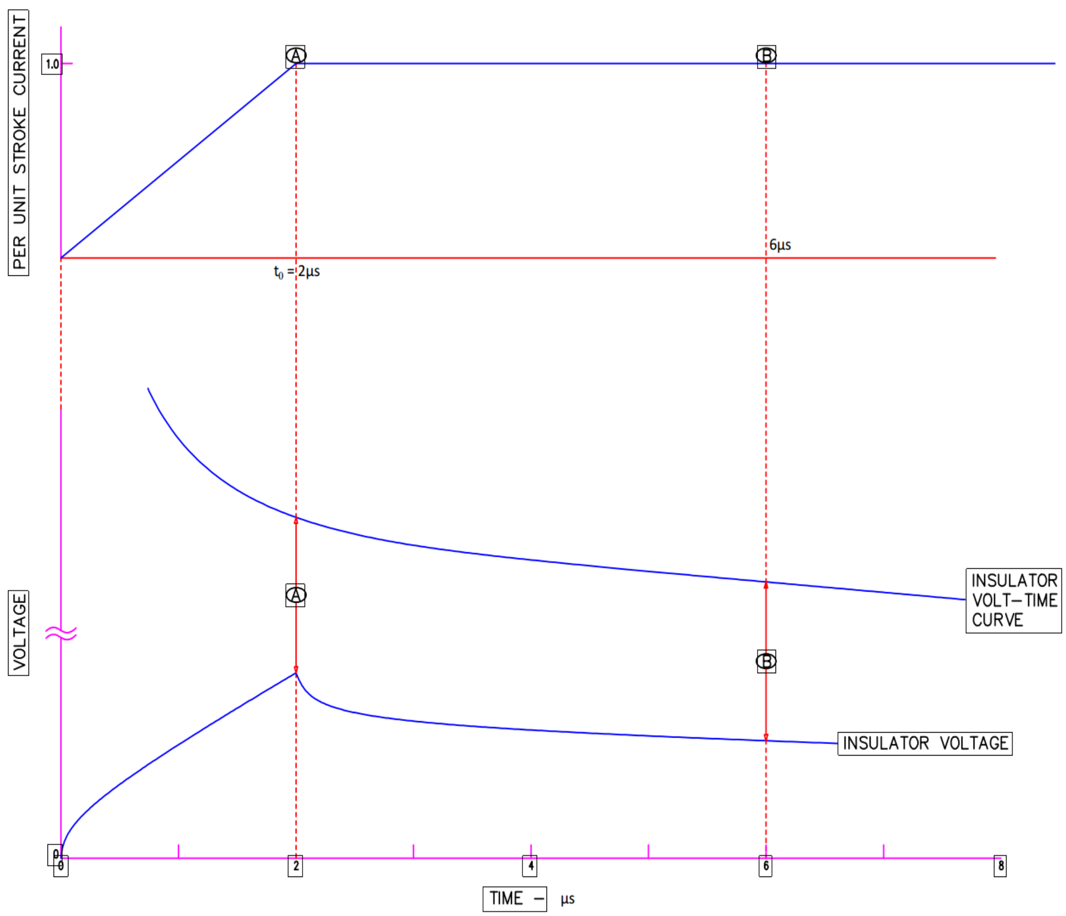

Fig. 4.2. A simple ramp function stroke current is used, and insulator voltages computed at only two points in time.

4.4.4 A Calculation for a double circuit

The schedules are provided to calculate lightning performance on the transmission line. The schedules are shown in the following;

1. Determine the arcing horn flashover voltage, $(V_I)_2$ at 2 µs in (kV) is calculated based on Equations (4.2).

$$(V_I)_2 = 820\ W \tag{4.7}$$

where $(V_I)_2$ is the arcing horn flashover voltage at 2 μs in (kV), and W is the arcing horn gap length in (m).

2. Determine the arcing horn flashover voltage, $(V_I)_6$ at 6 μs in (kV) is calculated based on Equations 4.8.

$$(V_I)_6 = 585\ W \tag{4.8}$$

where $(V_I)_6$ is the arcing horn flashover voltage at 6 μs in (kV), and W is the arcing horn gap length in (m).

3. Estimate the tower top voltage and average for all phases (kV) by (4.9).

$$(V_E)_T = 1.8\ (V_I)_2 \tag{4.9}$$

where $(V_E)_T$ is tower top voltage in (kV)

4. Compute the shield wire corona diameter in (m) by (2.6) and (2.7). Use height at the tower.

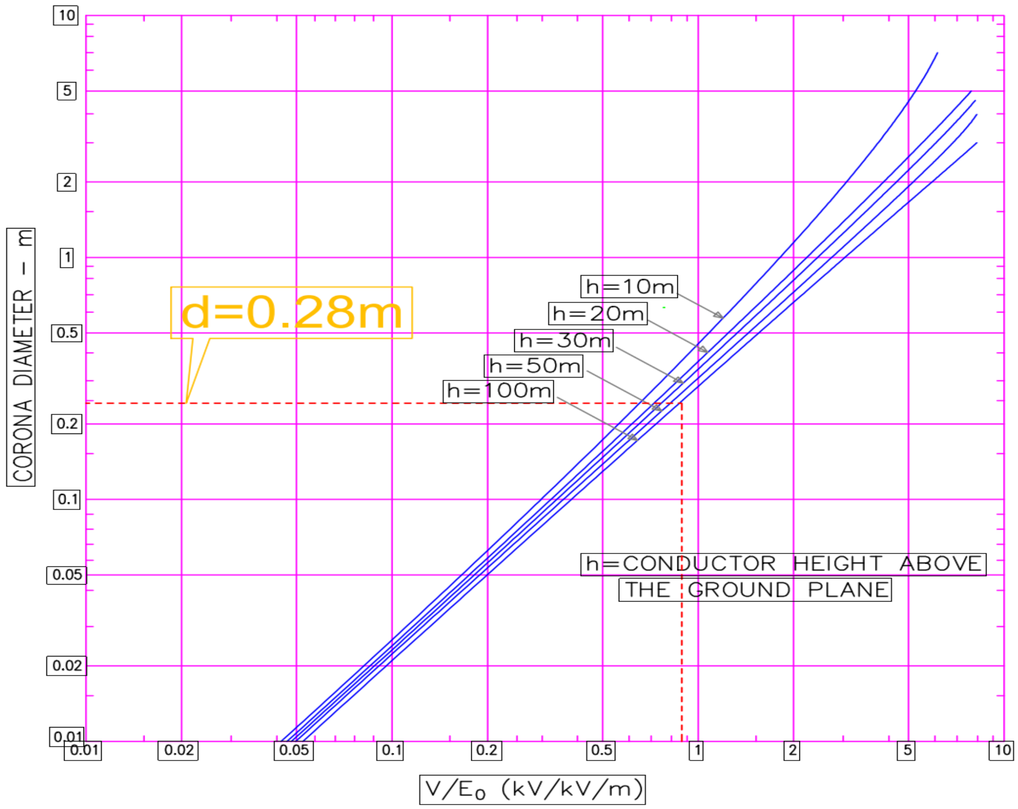

Fig. 4.3. Approximate diameter of the corona sheath around a conductor at high voltage.

The shield wire corona diameter estimated by using (2.6) is 0.28 m. The calculated result agrees with the approximate diameter of the corona sheath around a conductor at high voltage [1,2] in Figure 4.3.

5. Compute the self-surge impedance of each shield wire at the tower (Ω) by (2.7). The self-surge impedance of each shield wire at the tower, by using (2.7), is 458 Ω.

6. Compute the combined surge impedance, Z_S, of shield wire (the equivalent surge impedance of two shield wires) by (2.9) and (2.10). The equivalent surge impedance of two shield wires, by using (2.10), is 296 Ω.

7. Compute the coupling factor for each phase conductor, K_n, by (2.16). The coupling factors of the phase conductors, (upper, middle and lower) by using (2.16) are 0.4, 0.3, and 0.2, respectively.

8. The surge impedance of the towers, Z_t (Ω) is calculated by (2.13) [1]. The surge impedance of the towers is 174 Ω.

9. Determine tower travel time, τ_T (μs), by (4.10).

$$\tau_T = \frac{h_t}{c} \tag{4.10}$$

where τ_T is the tower travel time (μs), h_t is the tower height, by assuming, h_t is equal to 32.2 m, and c is the velocity of light (300 m/ μs), the tower travel time, τ_T is 0.11 μs.

10. Determine span travel time, τ_s (μs), by (4.11).

$$\tau_S = \frac{\text{span length}}{0.9\ c} \tag{4.11}$$

where τ_S is the span travel time (μs). By assuming span length is equal to 332.5 m, the span travel time τ_S is 1.23 μs.

11. Compute the travel time, τ_{pn} (μs) from tower top to each cross arm by (4.12.)

$$\tau_{pn} = \frac{Y_n}{300} \tag{4.12}$$

where τ_{pn} is the propagation time from the tower top to cross arm n, and Y_n is the distance from tower top to cross arm (m). The propagation time from the tower top to upper, middle and lower arms by using (4.12) are 0.01, 0.03, and 0.04 μs, respectively.

12. Select tower-footing resistance, R (Ω). R is selected based on the actual tower-footing resistance before and after the improvement of tower-footing resistance.

13. Compute the intrinsic circuit impedance, Z_I (Ω) by (4.13)

$$Z_I = \frac{Z_S Z_T}{Z_S + 2Z_T} \tag{4.13}$$

where Z_I is the intrinsic circuit impedance in Ω encountered by the stroke current at the instant it enters the equivalent circuit, Z_s is the equivalent surge impedance of two shield wires, and Z_t is the surge impedance of the tower (Ω). The intrinsic circuit impedance by using (4.13) is 80.01 Ω.

14. Compute the tower wave impedance, Z_W (Ω) by (2.18). The tower wave impedance is 58.32 Ω.

15. Compute the tower damping factor, φ by (2.19). The tower damping factor, is 0.065.

16. Complete the tower-footing resistance refraction factor, α_R by (4.14)

$$\alpha_R = \frac{2R}{Z_T + R} \tag{4.14}$$

The tower-footing refraction factor is 0.21.

17. Compute the per unit tower top voltage, $(V_T)_2$ at 2 μs by (4.15)

$$(V_T)_2 = \left[Z_I - \frac{Z_W}{1-\varphi}\,(1-\frac{\tau_T}{1-\varphi})\right] I \tag{4.15}$$

The tower top voltage per unit, $(V_T)_2$ at 2 μs is 24.8 kV.

18. Compute the reflected component at voltage $(V_T^{'})_2$ at the tower top from adjacent towers by (4.16).

$$(V_T^{'})_2 = \frac{-4K_S(V_T)_2^2}{Z_S}\left[\frac{1-2(V_T)_2}{Z_S}\right](1-\tau_S) \tag{4.16}$$

where K_S is the span attenuation factor (assume 0.85 unless better information is available). If $\tau_S > 1$ μs, there is no voltage reflection at 2 μs. The reflected component of voltage $(V_T^{'})_2$ at the tower top from adjacent towers by (4.16) is 0 kV.

19. The actual tower top voltage or the total tower top voltage magnitude is by (4.17).

$$(\overline{V}_T)_2 = (V_T)_2 + (V_T^{'})_2 \quad (4.17)$$

The actual tower top voltage or the total tower top voltage is 24.8 kV.

20. Compute the voltage $(V_R)_2$ across tower-footing resistance at 2 μs by (4.18).

$$(V_R)_2 = \left[\frac{\overline{\alpha}_R Z_I}{1-\varphi}\left(1-\frac{\varphi\tau_T}{1-\varphi}\right)\right] I \quad (4.18)$$

The voltage $(V_R)_2$ across tower-footing resistance at 2 μs, is 17.49 kV.

21. For each phase, compute the cross arm voltage, $(V_{pn})_2$ at 2 μs (kV) by (4.19).

$$\left(V_{pn}\right)_2 = (V_R)_2 + \frac{\tau_T - \tau_{pn}}{\tau_T}\left[(V_T)_2 - (V_R)_2\right] \quad (4.19)$$

where $\left(V_{pn}\right)_2$ is the voltage at cross arm n at 2 μs. The cross arm voltage, $(V_{pn})_2$ at 2 μs at the upper, middle and lower arms, are 23.9, 22.9, and 21.9 kV, respectively.

22. Compute the insulator voltage at 2 μs at the upper, middle and lower phase, $(V_{SN})_2$ (kV) by (4.20).

$$(V_{SN})_2 = (V_{pn})_2 - K_n(\overline{V}_T)_2 \quad (4.20)$$

where $(V_{SN})_2$ is the insulator voltage for phase n at 2 μs. The insulator voltage is the difference between the cross arm surge voltage and the phase conductor surge voltage. The insulator voltage for the upper, middle and lower phases at 2 μs are 13.2, 15.3, and 16.3 kV, respectively.

23. Compute the tower top voltage, $(V_T)_6$ at 6 μs without adjacent tower reflections by (4.21).

$$(V_T)_6 = (V_R)_6 = (V_{pn})_6 = \left[\frac{Z_S\,R}{Z_S+2R}\right] I \quad (4.21)$$

The tower top voltage, $(V_T)_6$ at 6 μs without adjacent tower reflections, is 17.6 kV.

24. Compute the reflected voltage component, $(V_T')_6$ from adjacent tower at 6 μs by (4.22).

$$(V_T')_6 = -4K_S\,Z_S\left(\frac{R}{Z_S+2R}\right)^2\left[1-\frac{2R}{Z_S+2R}\right] I.. \quad (4.22)$$

The reflected voltage component, $(V_T')_6$ from the adjacent tower at 6 μs, is -3.1 kV.

25. Compute the total per unit insulator voltages for each phase, $(V_{SN})_6$ at 6 μs by (4.23).

$$(V_{SN})_6 = \left[(V_T)_6 + (V_T')_6\right](1-K_n) \quad (4.23)$$

The insulator voltages for the upper, middle and lower phases, $(V_{SN})_6$ at 6 μs, are 8.3, 10 and 11.2 kV, respectively.

26. Compute the ratios of voltages between Steps 1 and 22 for the upper, middle and lower phases. This will be $(I_{cn})_2$, the critical stroke current required for flashover at 2 μs by (4.24).

$$(I_{cn})_2 = \frac{820\ W}{(V_{SN})_2} = \frac{(V_I)_2}{(V_{SN})_2} \quad 4.24)$$

The critical stroke current required for flashover at 2 μs at the upper, middle, and lower phases are 56, 48, and 45 kA, respectively.

27. Compute the ratios of voltage between Steps 1 and 25 for the upper, middle, and lower phases. This will be $(I_{cn})_6$, the critical stroke current required for flashover at 6 μs by (4.25).

$$(I_{cn})_6 = \frac{820\ W}{(V_{SN})_6} = \frac{(V_I)_6}{(V_{SN})_6} \quad (4.25)$$

The critical stroke current required for flashover at 6 μs at the upper, middle, and lower phases are 64, 52 and 47 kA, respectively.

28. For each phase, select the lowest of the currents in Steps 26 and 27 as (I_{cn}).

29. For each value of I_{cn} in Steps 28, select the voltage, V_{cn}, that goes with it from Steps 1 and 2 (kV).

30. Plot I'_{cn} for the upper, middle, and lower phases for a full 360° by (4.26).

$$(I'_{cn})_2 = \left[\frac{820\ W - V_{on}\sin(\theta_n - \alpha_n)}{(V_{SN})_2}\right](I_{cn})_2 \tag{4.26}$$

where $(I_{cn})_m$ is the critical stroke current required to cause flashover of insulator n at m μs with power frequency voltage present. V_{on} is the crest phase to ground voltage for phase n, θ_n is the instantaneous voltage angle, α_n is the phase angle of phase n (either 0° - 120°, or + 120°).

31. Determine percent of time each phase is dominant by (4.27).

$$(\text{phase dominant})_n = \frac{(\theta_2 - \theta_1)}{360}\ 100\% \ldots\ldots \tag{4.27}$$

32. Compute the average value of I'_{cn} for each phase (the upper, middle, and lower phases) during the time it, is dominated, by (4.28).

$$\bar{I}_{cn} = I_{cn}\left\{1 + \frac{V_{on}}{V_{cn}}\left[\frac{\cos(\theta_2 - \alpha_n) - \cos(\theta_1 - \alpha_n)}{\theta_2 - \theta_1}\right]\right\} \tag{4.28}$$

where $(\theta_2 - \theta_1)$ must be in radians. The average value of $\bar{I}_{cn}$ for the upper, middle, and lower phases is 46.8, 39.3 and 37 kA, respectively.

33. Find the probability that stroke current in Steps 33 will be exceeded in any flash to the line by (2.5). The probability that stroke current by using (2.5) at upper, middle and lower phases are 0.3, 0.4 and 0.4.

34. Compute the relationship for the number of flashovers to the line by (4.29).

$$N_S = N_L = 0.012\,T\,(\,b + 4h_t^{1.09} \qquad (4.29)$$

where N_L is the number of flashovers to the line per 100 kilometers per year and T is the keraunic level in thunder-days per year. The number of flashovers to the line per 100 kilometers per year is 548.4 flashes/100 km-year.

35. Calculate the back-flashover rate, BFR, given as the product of this probability and the number of strokes that terminate on the towers. For simplicity, the number of strokes to the towers is assumed to be 60% of all strokes to the line as in (4.1). The number of trip-out rates at upper, middle and lower arms were 27.4, 34.6 and 47.2, respectively.

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5

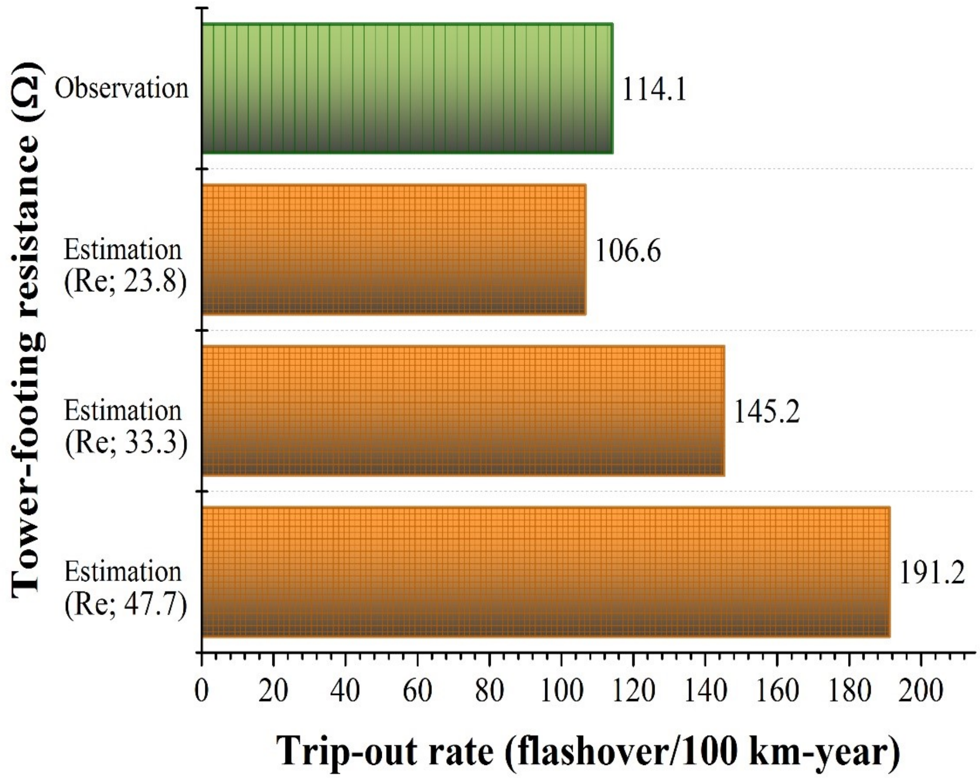
Results and Discussion

5.1 Overview

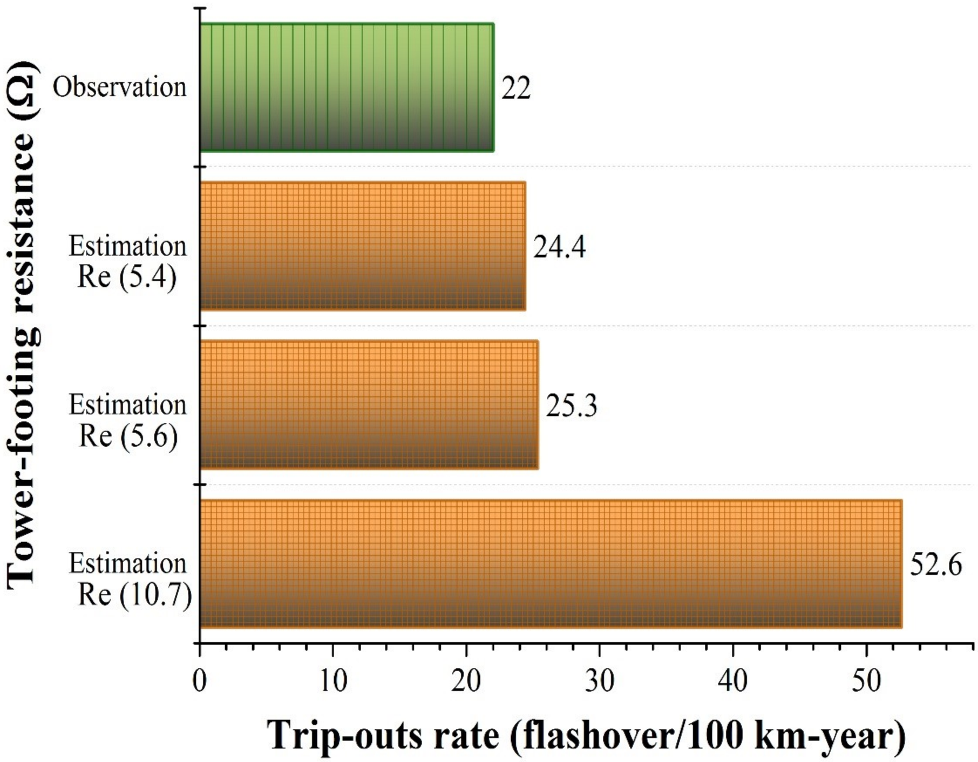
The IEEE Flash program has been developed to estimate the lightning performance of overhead line transmission line [1,2]. The numerical simulations were done according to IEEE Flash program and IEEE method [3]. The lightning trip-out rate was calculated in the forward problem based on the analytical method [1] and the IEEE flash program. The results investigation are almost the same with the simulation results.

5.2 Trip-out rates

Figure 5.1 (a) and (b) shows the comparison of observed trip-out rates with the analysis by the IEEE FLASH program version 1.81. The IEEE Flash program recommends to use tower-footing resistance measured at low frequency, because this value can be measured easily [1]. In the analysis, the average tower-footing resistance with the flashover (47.7 or 10.7 Ω) and the average tower footing resistance at towers No. 1–140 (33.3 Ω or 5.6 Ω) are used, respectively. The average impulse resistance of towers, the reduced resistance of the towers due to the ionizing effect before and after the improvement is set 23.8 Ω and 5.4 Ω, respectively, by assuming the impulse resistance is about 50% of the low-current value [2,3,4]. The impulse resistance is also used in the analysis. The trip-out rates by the IEEE Flash program are in good agreement with the observation result before and after the improvement of the tower-footing resistance when the impulse resistance of the tower is used in the analysis. Meanwhile, the observation result is lower than the trip-out rates by the IEEE Flash in other case.



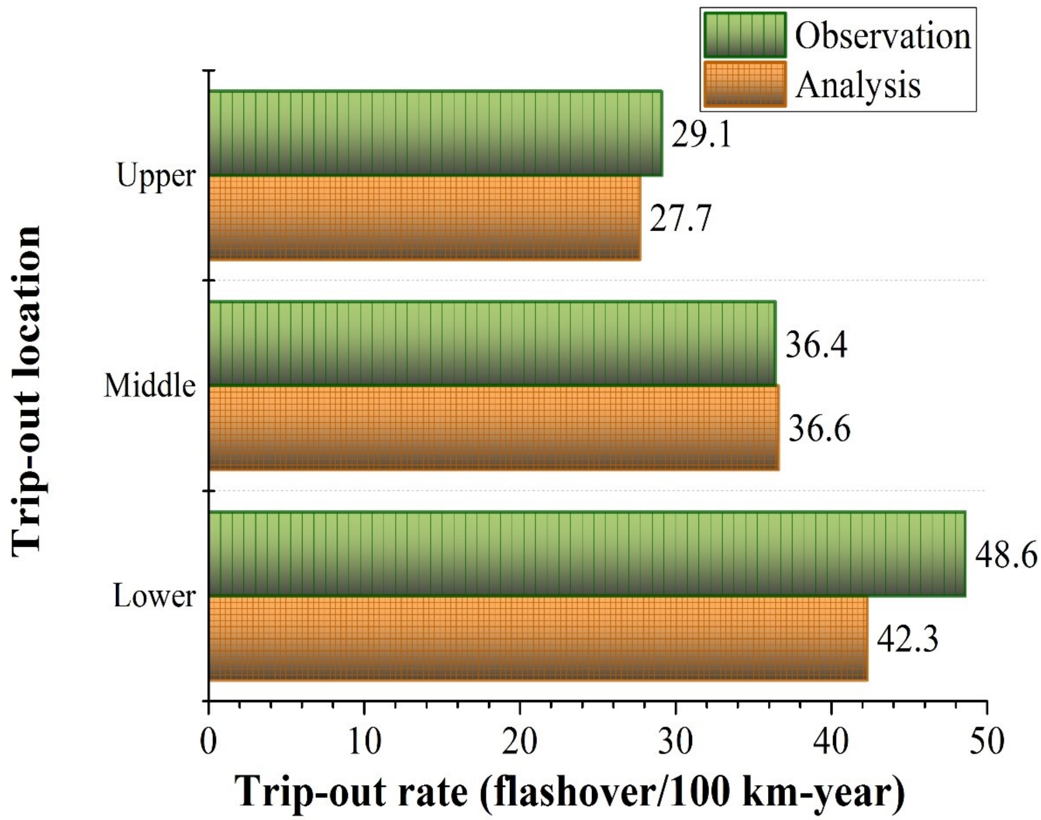
(a) Trip-out rates before improvement of tower-footing resistance.



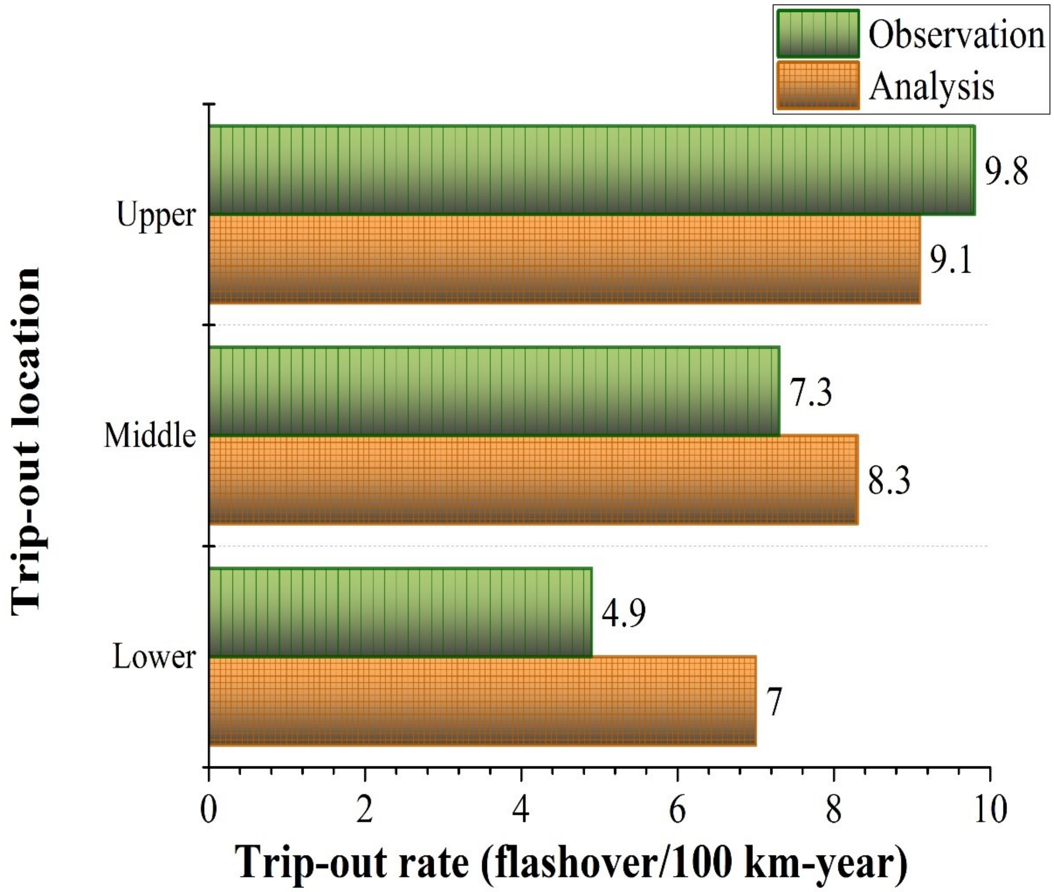
(b) Trip-out rates after improvement of tower-footing resistance.

Fig. 5.1. Trip-out rates by the IEEE FLASH program with lightning trip-outs observation before (a) and after (b) improvement of tower-footing resistance (Re).

Figure 5.2 shows the dependence of trip-out rates on arm location. The calculated results agree fairly well with the observation of lightning trip-out rate. From these results, it is shown that IEEE Flash program and the IEEE method provides good estimates of the trip-out rates for the line under study by taking into consideration of the ionizing effect.



(a) Trip-out rates before improvement of tower-footing resistance.



(b). Trip-out rates after improvement of tower-footing resistance.

Fig. 5.2. Dependence of trip-out rates on arm location.

5.3 Proposal for decrease of trip-out rates

Figure 5.3 shows the trip-out rate calculated by using the IEEE FLASH program considering the tower-footing resistance from 1 to 12 Ω and the length of an arcing horn gap from 0.9 to 1.3 m. The trip-out rate increases with the decrease of the length of an arcing horn gap and the increase of tower-footing resistance. This is because when the tower footing resistance is high, the insulator voltage is also high and the time to flashover is shortened so that the critical flashover voltage occurs easily. When the tower-footing resistance at all towers is set to be 10 Ω, which corresponds to the resistance of 5 Ω under lightning impulse currents in Fig.8, the trip-out rate becomes less than 10 flashover/100 km-year when the length of an arcing horn gap is set to be longer than 1.2 m.

As is shown in [5], the insulator damage at the tower with the length of an arcing horn gap longer than 1.4 m is reported even when the tower-footing resistance is less than 10 Ω. In the actual insulation design, it is important to compare the v-t characteristics of the insulators and the arcing horn gap [6].

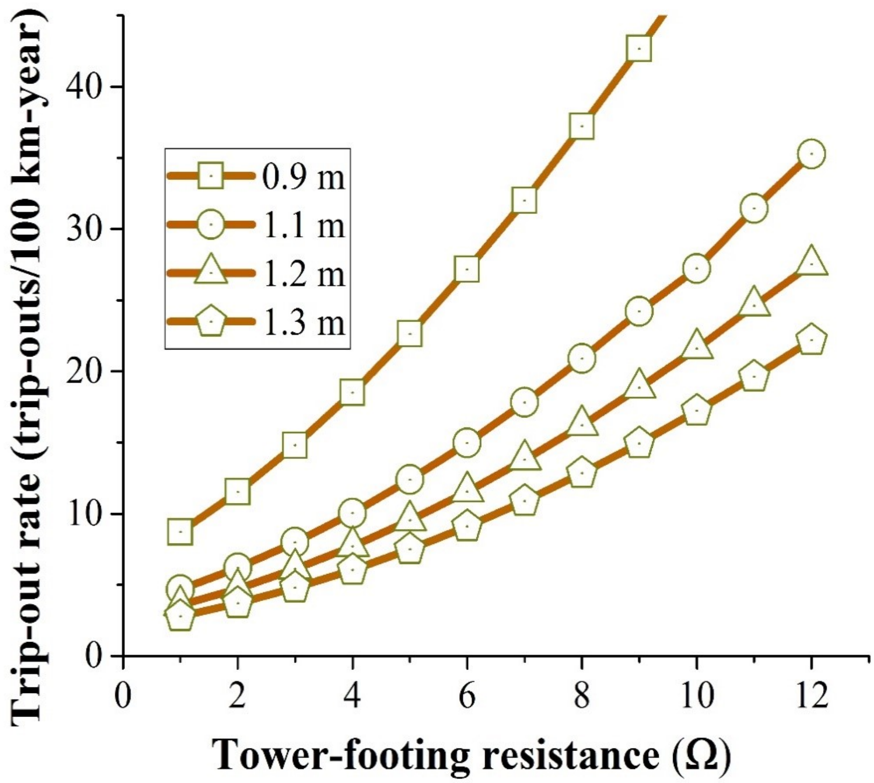


Fig. 5.3. Dependence of rate of trip-outs on tower-footing resistance and length of arcing horn gap.

5.4 A numerical example for double circuit transmission line

5.4.1 Calculation of the back-flashover rate

Calculation of the back-flashover is not a straightforward process and requires many aspects to be considered. Computer software using IEEE Flash method is one way of completing the calculation. Anderson [2] outlines a simplified process that enables a hand calculation of the back-flashover using the two-point method. This method has been shown in chapter 4.

5.4.2 Back-flashover rate of the 150 kV transmission line Payakumbuh – Koto Panjang in West Sumatra in Indonesia

The method is used to indicate how trip-out rate increases as tower-footing resistance increases. This method is also useful to study the trip-out rate dependent on the location of phase conductors, not obtained by the IEEE Flash program. The trio-out rate for the 150 kV transmission line of Payakumbuh - Koto Panjang has been calculated around an average tower-footing resistance of 20 Ω, the length of an arcing horn gap 0.9 m, tower height 32.2 m, spacing between shield wires 7 m, span length 332,5 m, conductor sag 7 m, and tower width at base 5 m. Table 5.1 shows data sheet of the vertical double circuit, two ground wires. Microsoft Excel has been used for the calculation process with the input and output details shown in Table 5.2. For the reader's convenience, the calculation process has been included.

Table 5.1 data sheet of vertical double circuit two ground wires.

Conductor No.	Function	Phase coordinates		Conductor Radius (cm)	Bundle spacing	Operating P - P	α Phase angle (°)
		X (m)	Y (m)				
1	Shield	-3.5	32.2	0.48	-	0	-
2	Shield	3.5	32.2	0.48	-	0	-
3	A	-3.8	28.1	1.28	47	150	0
4	B	-4.0	23.8	1.28	47	150	-120
5	C	-4.2	19.5	1.28	47	150	120
6	C′	3.8	28.1	1.28	47	150	120
7	B′	4.0	23.8	1.28	47	150	120
8	A′	4.2	19.5	1.28	47	150	0

Table 5.2 The calculation process by two-point method

Two Point Method									
Back-Flashover Rate									
No.	**Procedure**	**Figure or**	**Compute Value for Phase**						
		Equation	**ALL**	**Upper/A**	**Middle/B**	**Lower/C**	**Lower/C'**	**Middle/B'**	**Upper/A'**
1	Determine insulator flashover voltage,	Eq. 4.7							
	(VI)2 at 2 ms (kV)			**740**	**740**	**740**	**740**	**740**	**740**
2	Repeat step 1 at 6 µs	Eq. 4.8		**527**	**527**	**527**	**527**	**527**	**527**
3	Multiply step 1 values by 1.8 for estimate								
	of tower top voltage and average for all tower	Eq. 4.9	**1332**						
4	Using step 3 voltage and Eo = 1500 kV/m, compute	Figure 4.3							
	shield wire corona diameter (m). Use height at tower	Eq. 2.6							
		Eq. 2.7	**0.89**						
			1.52						
			0.28						
5	Using step 4 results, compute self-surge impedance	Eq. 2.7	**458**						
	of each shield wire at tower								
6	Using step 5 results, compute combined surge impedance,								
	Zs, of shield wire	Eq. 2.9	134						
		Eq. 2.10	**296**						
7	Compute coupling factors to each phase conductor, Kn	Eq. 2.16							
		Zn1		155.9	105.1	75.8	75.8	105.1	155.9
		Zn2		98.5	76.0	57.5	57.5	76.0	98.5
		Kn		**0.4**	**0.3**	**0.2**	**0.2**	**0.3**	**0.4**
8	Determine tower surge impedance (ZT) W	Eq. 2.16	**174**						
9	Determine tower travel time tT ms	Eq. 4.10	**0.11**						
10	Determine tower travel time ts ms								
		Eq. 4.11	**1.23**						
11	Compute travel time tpn								
		Eq. 4.12		**0.01**	**0.03**	**0.04**	**0.04**	**0.03**	**0.01**
12	Select footing resistance (actual data)		**20**						
	in figure 12.5.12								
13	Compute instrinsic circuit impedance ZI W	Eq. 4.13	**80.01**						
14	Compute tower wave impedance ZW W	Eq. 2.18	**58.32**						
15	Compute tower damping factor j	Eq. 2.19	**0.065**						
16	Complete footing resistance refraction factor aR	Eq. 4.14	**0.21**						
17	Compute per unit tower top voltage, (VT)2 at 2 µs	Eq. 4.15	**24.8**						
18	Compute the reflected component at voltage (V'T)2 at the	Eq. 4.16	**0.00**						
	tower top from adjacent towers								
19	Add step 17 and 18 to find actual tower top voltage,	Eq. 4.17	**24.8**						
	(VT)2 (kV)								
20	Compute voltage (VR)2 across footing resistance at 2 ms	Eq. 4.18	**17.49**						

	Two Point Method								
	Back-Flashover Rate								
21	Reduce (VR)2 by same proportion that step 19 was reduced								
	from step 17to find actual footing resistance voltage, (VR)2								
	at 2 µs (kV)		**17.49**						
22	For each phase, compute the crossarm voltage,	Eq. 4.19		**23.9**	**22.9**	**21.9**	**21.9**	**22.9**	**23.9**
	(Vpn) at 2 ms (kV)								
23	Using results from step 7, 19 and 22, compute each perunit	Eq. 4.20		**13.2**	**15.3**	**16.3**	**16.3**	**15.3**	**13.2**
	insulator voltage at 2 ms, (VSN)2 (kV)								
24	Compute tower top voltage, (VT)6 at 6 ms without adjacen	Eq. 4.21	**17.6**						
	tower reflection								
25	Compute the reflected voltage component, (V'T)6 from	Eq. 4.22	**-3.1**						
	adjacent tower reflections								
26	Using the voltages in steps 24and 25 and coefficient of								
	coupling in step 7, compute total per unit insulator voltages	Eq. 4.23		**8.3**	**10.0**	**11.2**	**11.2**	**10.0**	**8.3**
	for each phase (VSN)6								
27	Compute ratios of voltages between step 1 and 23 for each								
	phase. This will be (Icn)2, the critical stroke current required								
	for flashover at 2 ms	Eq. 4.24		**56**	**48**	**45**	**45**	**48**	**56**
28	Compute ratios of voltage between step 2 and 26 for each								
	phase. This will be (Icn)6, the critical stroke current								
	required for flashover at 6 ms	Eq. 4.25		**64**	**52**	**47**	**47**	**52**	**64**
29	For each phase, select the lowest of the current in step 27			**56**	**48**	**45**	**45**	**48**	**56**
	and 28 as ICN								
30	For each value of ICN in step 29, select the voltage, VCN,								
	that goes with it from steps 1 and 2 (kV)			**740.0**	**740.0**	**740.0**	**740.0**	**740.0**	**740.0**
31	Using step 29 and 30, plot I'CN for each phase for a full 360°								
32	From work sheet 2-A, determine percent of time	Eq. 4.26		9.8	18.0	22.0	22.0	18.0	9.8
	each phase dominated								
33	Compute average value of I'CN for each phase during	Eq. 4.27							
	the time it is dominated			**46.8**	**39.3**	**37.0**	**37.0**	**39.3**	**46.8**
34	Find probability that stroke current in step 33 will be	Eq. 4.28		**0.3**	**0.4**	**0.4**	**0.4**	**0.4**	**0.3**
	exceeded in any flash to the line								
35	Multiply line flashes in schedule 1 step 25 by 0.6 to establis	Eq. 12.4.6	**131.79**						
	effective tower flashes per 100 km per year								
36	Multiply step 35 by values in step 32 and divide by 100			**12.9**	**23.7**	**29.0**	**29.0**	**23.7**	**12.9**
	to find tower flashes per phase per 100 km year								
37	Mutiply each values in step 36 by the corresponding								
	probability in step 34 to find expected number of strokes			**13.70**	**17.30**	**23.60**	**23.60**	**17.30**	**13.70**
	causing flashover of a given phase								
38	Sum all values instep 37 for total back-flashover per 100 km								
	per year								
	TOTAL			**109.20**					

5.5 Effects of line parameters of 150 kV Payakumbuh – Koto Panjang in West Sumatra in Indonesia

5.5.1 Tower-footing resistance

Figure 3.6 shows the trip-out ratio increases with the increase of the tower-footing resistance. Equations (4.13) to (4.28) and Step 14 to 33 in Table 5.2 show the influence of the tower-footing resistance on the tower top voltage. The lower the tower-footing resistance is, the more negative are the reflections produced from the tower base toward the tower top, which lower the crest voltage of the tower top voltage. The lower the resistance of the tower footing, the more negative the resulting reflection from the base of the tower towards the top of the tower, which lowers the peak voltage of the tower top.

5.5.2 Span length

Figure 3.7 shows the trend that the trip-out ratio becomes high with the increase of the span length, which is significant after the improvement of the tower-footing resistance. Equations (4.15) to (4.16) and step 17 to 18 in Table 5.2 show that the influence of the span length on the tower top voltage. In the case of the high tower-footing resistance the flashover occurs prior to the arrival of the wave reflected from the adjacent towers due to the high potential rise of the tower.

5.5.3 Altitude of towers

Figure 3.8 shows that the degree of the influence of the altitude of the tower is not significant on the transmission line under study. In [2] altitude of towers, parameter is not accounted into the calculation, so the effect of towers altitude does not appear.

5.5.4 Height difference of towers top

Figure 3.9 shows that the difference of the tower top is not a dominant factor on the transmission line under study. In [2] height difference of towers top is not also accounted into the calculation, so the affected of height difference of towers top does not appear.

5.5.5 Length of an arcing horn gap

Figure 3.10 shows that the flashover voltage decreases with the decrease of the length of an arcing horn gap. Equations (4.7) to (4.8) and Step 1 to 2 in Table 5.2 show the influence of the length of an arcing horn gap on the trip-out rate. The length of an arcing horn gap is a dominant factor on the transmission line.

5.6 Location of flashover

Figure 3.11 shows that the trip-out rate is dependent on the location of the line. It explains that the insulator voltage on the circuit I is high due to the topology. In [2], the height difference of tower tops is not also counted into the calculation, so the effect of the height difference of tower tops does not appear.

Figure 3.12 show the trip-out rate as a function of the location flashover. The percentage of time that each phase is dominant (most likely to flashover first) is determined based on the calculated critical stroke current in Figure 5.6.

Besides that, the average value of critical current $(I'_{cn})_2$ in Equation (4.26) or step 32 in Table 5.2 for that phase during that time is used to compute the ultimate trip-out rate.

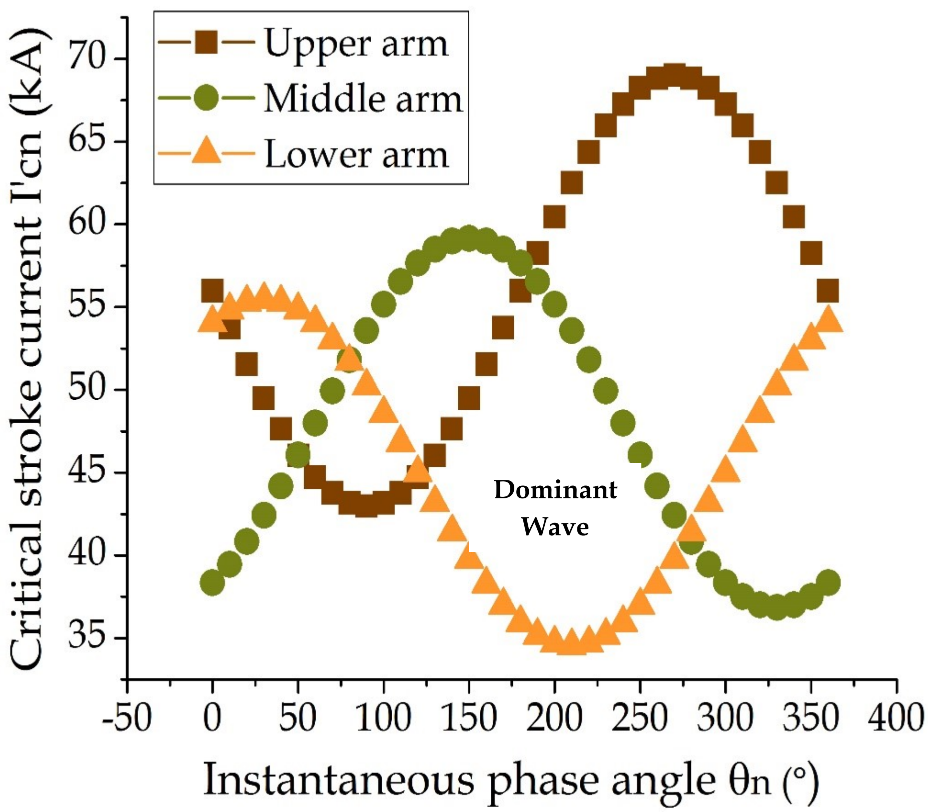


Fig. 5.6. Fluctuation of the critical stroke current I'_{cn} required to cause flashover of phase n.

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6

Conclusion

6.1 Conclusion

In this thesis, the results lightning trip-out in West Sumatra in Indonesia are presented. It is shown that main cause of the trip-outs is lightning, 66% of all trip-outs. Main conclusions are as follow:

The lightning trip-out rates of the studied line are significantly affected by the tower-footing resistance and the length of an arcing horn gap for the transmission lines under study.

The trip-out rates calculated by taking account of the reduction of the tower-footing resistance due to the ionizing effect agree well with the observed ones. This indicates the importance of the impulse resistance in the analysis of the lightning performance of the line.

The trip-out rate at the lower arm is high for the cases of the average grounding resistance of 33.3 ohms, and the rates at the lower arm are high for the cases of the average grounding resistance of 5.6 ohms. Such trend can be simulated by the IEEE method using the impulse resistance.

The trend that trip-out ratio becomes high with the increase of the span length is significant after improvement of the tower-footing resistance. However, the trend is weak before improvement of the tower-footing resistance. This is because in the case of the high tower-footing resistance the flashover occurs before the arrival of the wave reflected from the adjacent towers due to the high potential rise of the tower. Therefore, the degree of the influence of the span length on the trip-out ratio is dependent on the tower-footing resistance.

The local lightning activity significantly affects by the trip-out rate. The high rate of lightning trip-out before and after the improvement of the tower-footing resistance is seen in circuit I. This is due to the placement of circuit I on the north side from No. 1 to 37 towers and on the east side from No. 38 to No. 140 towers this area, the thunderstorm often approaches the line and the towers from the northeast.

The trip-out rate of the line under study can be reduced to less than half of the present rate, 22 flashover/100 km–year, if the tower-footing resistance at all towers is set to less than 10 Ω and the length of an arcing horn gap is set to longer than 1.2 m.

6.2 Recommendation

We have successfully investigated and estimated the lightning trip-out on transmission line under study based on the two-point method and IEEE Flash program. To obtain practical results, analysis by considering another parameter, for example an altitude of the tower and topography condition of transmission line, might be important.

Acknowledgement

I'm grateful to Allah. I can complete finishing this thesis, and I hope this study will be useful for me and other people related to this work that will make this study more helpfull. I would like to express my gratitude to all those people who assist me to prepare and complete this study.

First and foremost, I am very thankful to my supervisor Prof. Koji Michishita for his valuable supervision, advice, and support during my doctoral study at Shizuoka University. He has been supportive since the days I came to Japan to till date. He has been supported me academically and emotionally through the rough road to finish this thesis. I would also like to extend my apreciation to Prof. Yokoyama his advices during my doctoral study.

Second, I am grateful to all thesis reviewers for reviewing this work. I would like to thank all members of Michishita laboratory for their assist and discussion in the laboratory.

Third, I would like to acknowledge Directorate General of Resources for Research, Technology and Higher Education and the Padang

Institute of Technology (ITP) for the financial support throughout my study.

Last but not the least, special thanks to my big family, my husband (Mendriadi), and my sons (Muhammad Naufalun Nabil and Muhammad Naufalul Lutfi) for their endless love, support, and encouragement. They are always motivating me to reach my dreams, supporting my way of life and study.

Research Activity:

Scientific papers:

1. Yusreni Warmi and Koji Michishita, "Investigation of Lightning Trip-out on 150 KV Transmission Line in West Sumatra in Indonesia", IEEJ Transaction on Electrical and Electronic Engineering, Vol.11, Issue.5, Page: 671 – 673, Year: 2016.

2. Yusreni Warmi and Koji Michishita "Tower-footing Resistance and Lightning Trip-outs of 150 KV Transmission Lines in West Sumatra in Indonesia", International Review of Electrical Engineering (IREE), Vol 12, No 3, ISSN 1827 - 6660(2017), May – June 2017 pages (260-266).

International Conferences:

1. Yusreni Warmi and Koji Michishita, "Investigation of Lightning Performance on 150 kV Transmission Line in West Sumatra", 9th Asia-Pacific International Conference on Lightning (APL 2015), 23 - 27 June 2015, Nagoya, Japan.

2. Yusreni Warmi and Koji Michishita, "A Study on Lightning Outages on 150 kV Transmission Line of Payakumbuh-Koto Panjang in West Sumatra in Indonesia", 19th International Symposium on High Voltage Engineering (ISH 2015), 23 – 28 August 2015, Pilsen, Czech Republic.

3. Yusreni Warmi and Koji Michishita, "Horn Length Estimation for Decrease of Trip-out Rates on 150 kV Transmission Line in West Sumatra in Indonesia", Joint Conference of The thenth International Workshop on High Voltage Engineering (IWHV 2016) and 2016 Japan-Koroea Joint Symposium on Electrical Discharge and High Voltage Engineering (JK 2016 on ED & HVE), ED–16–127, SP–16–056, HV–16–112, Miyazaki, Japan (2016.11.4).

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1. Yusreni Warmi and Koji Michishita, "Effect of Grounding Resistance on Trip-outs of 150 kV Transmission Line in West Sumatra in Indonesia", The 2016 Annual Meeting of The Institute of Electrical Engineering of Japan, 16 – 18 March 2016, Sendai, Japan.