

Tower-Footing Resistance and Lightning Trip-outs of 150 kV Transmission Lines in West Sumatra in Indonesia

Yusreni Warmi^{1,*}, and Koji Michishita²

¹Padang Institute of Technology, Padang, West Sumatra, Indonesia

²Graduate School of Science and Technology, Shizuoka University, Hamamatsu, 4328561, Japan

Abstract. The trip-out rates calculated by taking account of the reduction in 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 a trend can be simulated by the IEEE method using the impulse resistance. The trend for the trip-out ratio to become high with the increase in 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.

1 Introduction

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 addition 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]. In this paper, 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, namely 20 to 40 flashes/100 km-year [19] for the 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].

* Correspondence to: Yusreni Warmi. E-mail: yusreni@itp.ac.id

^{*} Padang Institute of Technology, Padang, West Sumatra, Indonesia.

2 Transmission Line under Study

2.1 Line configuration

The location of the transmission line under study in West Sumatra is shown in Figure 1. 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]. In figure 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. The thunderstorm in this area often moves from the northeast to the southwest.



Fig. 1. Location of Transmission line under study.

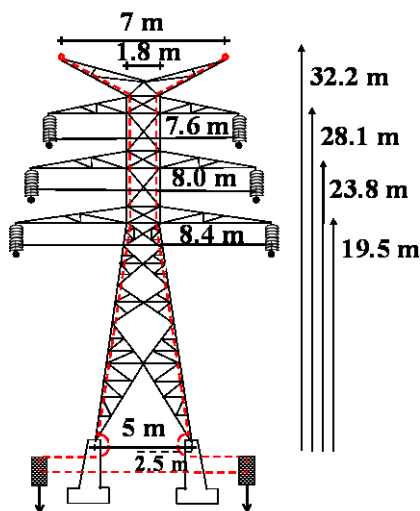


Fig. 2. Configuration of representative tower.

Fig. 2 shows the configuration of one of four types of towers with almost the same dimensions [22]. 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.

Table 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 [19,22,23]. 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.

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Table 1. Line condition.

	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

Figure 3. Shows the distribution of the length of an arcing horn gap installed at each tower [22,23]. 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 [22,23]. 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

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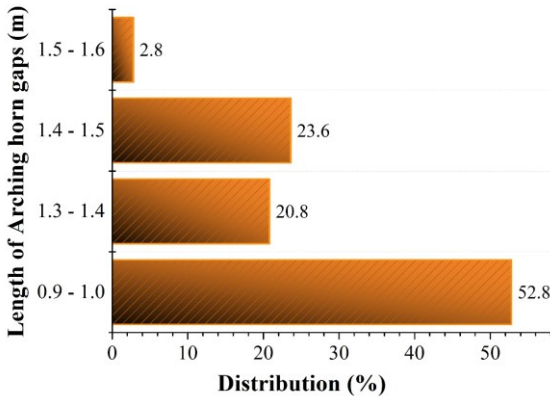


Fig. 3. Distribution of the length of an arcing horn gap from No. 1 to No. 140 towers [22]

2.2 Tower-footing resistance

Figure 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 before and after the improvement were 3.3 and 1.8 years, respectively.

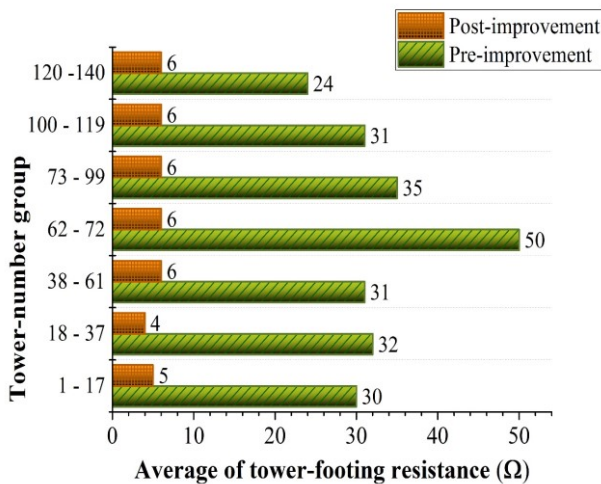


Fig. 4. Measurement data of average value of tower-footing resistance at No. 1 to No 140 towers.

3. Factor Influencing Lightning Trip-outs

3.1 Lightning activity

Figure 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.

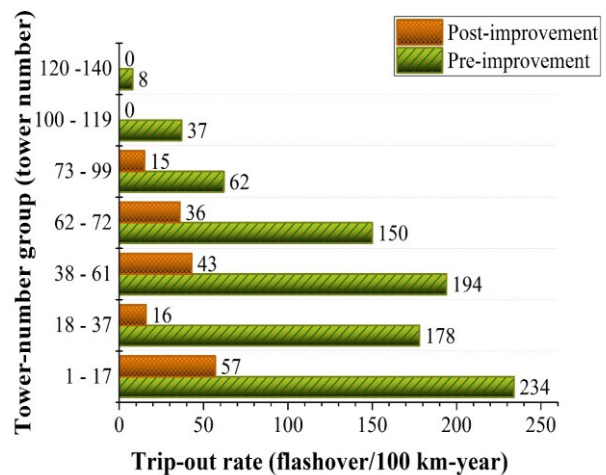


Fig. 5. Trip-outs rate as a function of the tower-number group.

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.

3.2 Tower-footing resistance

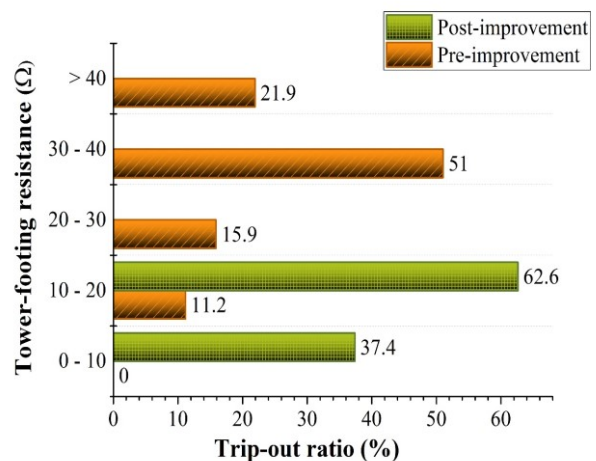


Fig. 6. Trip-out rate as a function of tower-footing

Figure 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 2. 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.

Before the improvement of tower-footing resistance, the highest number of flashover was found at No. 16 tower with the tower-footing resistance of 35 Ω and the average tower-footing resistance at the towers experiencing flashover was 48 Ω. After the improvement of the tower-footing resistance, the highest number 2 times, was found at 7 towers (No. 10, 16, 19, 46, 50 and 61 towers with the tower-footing resistance of 10 Ω and No. 47 tower with the tower-footing resistance of 15 Ω) and the average tower-footing resistance of the towers with flashover was 11 Ω.

Table 1. 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

3.3 Span Length

Figure 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.

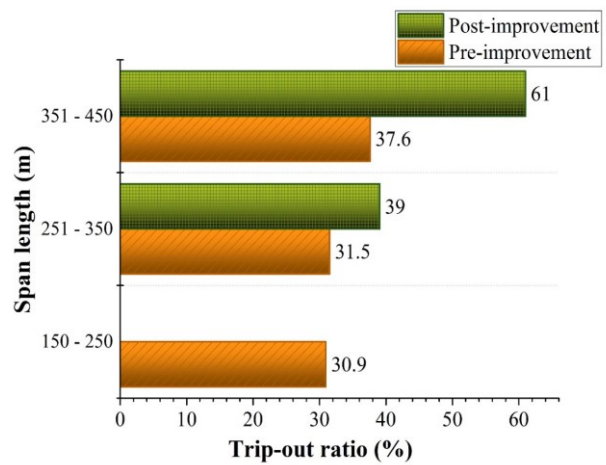


Fig. 7. Trip-outs rate as a function of the span length.

3.4 Altitude of towers

Figure 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 [20]. However, such a trend can't be seen in Fig. 8 because the altitude of 6 towers out of 10 in Table 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.

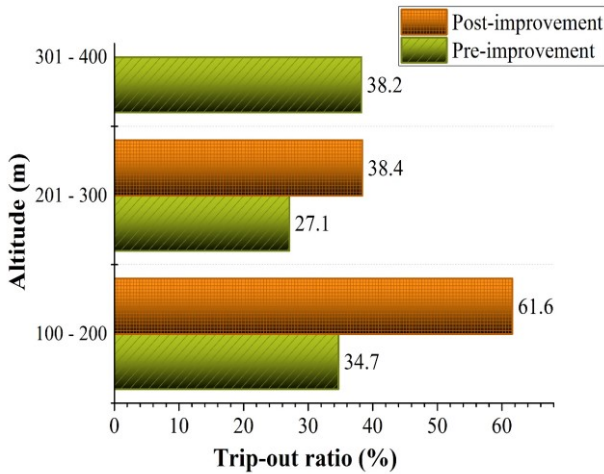


Fig. 8. Trip-outs rate before and after improvement as a function of the altitude.

3.5 Height difference of tower tops

Figure 9. Shows the trip-out ratio as a function of the height difference of the tower top. The height difference of tower tops is calculated as the average difference between 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 the difference of the tower-top height, the higher the trip-out ratio [20]. 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 the investigation shows that the difference of the tower top is not a dominant factor on the transmission line under study.

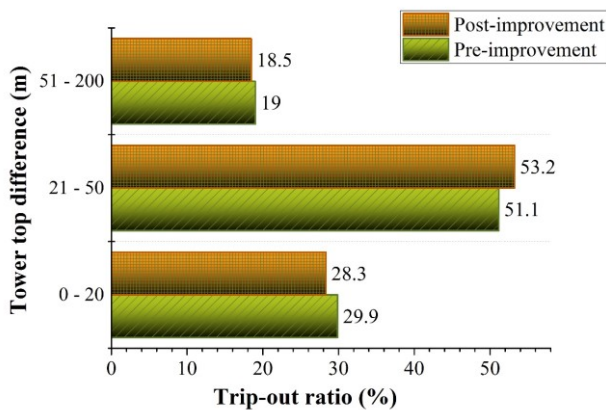


Fig. 9 Effect of tower-height difference on the trip-out ratio.

4. Location of Flashover

Figure 10. 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.

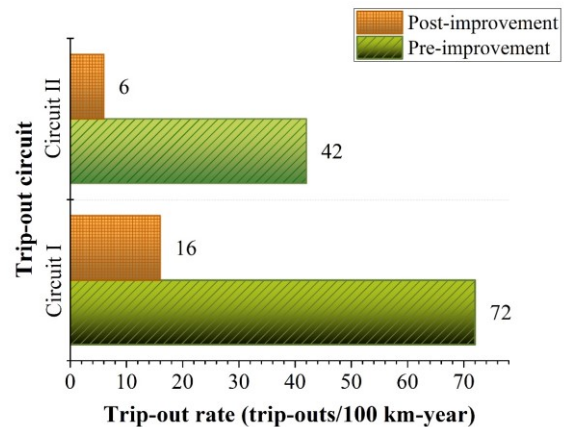


Fig. 10 Rate of trip-outs for circuits I and II.

5. Analysis

5.1 Method of analysis

The critical current resulting in the flashover is evaluated at two times, namely two μs and $6\mu\text{s}$, as in the case of the IEEE FLASH program by assuming the front duration of the lightning current two μs . Such a simplified method is used because the objective of this thesis is to Improve the lightning protection design of the transmission line. In the process, 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 a straightforward method (four parallel), 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].

$$CFO = \left(400 + \frac{710}{t^{0.75}} \right) D \quad (1)$$

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

5.2 Line model and lightning incidence to transmission line

A 47 km-long double-circuit line with the span length of 333 m, simulating the range 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/.

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].

$$BFR = 0.6 N_S P(I_C) \quad (2)$$

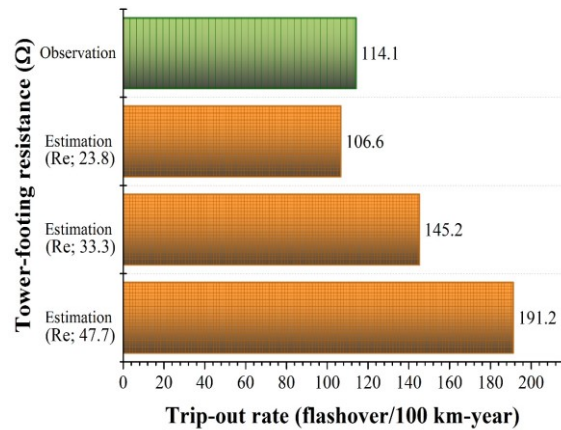
where I_C is the critical current resulting in back-flashover.

6. Results and Discussion

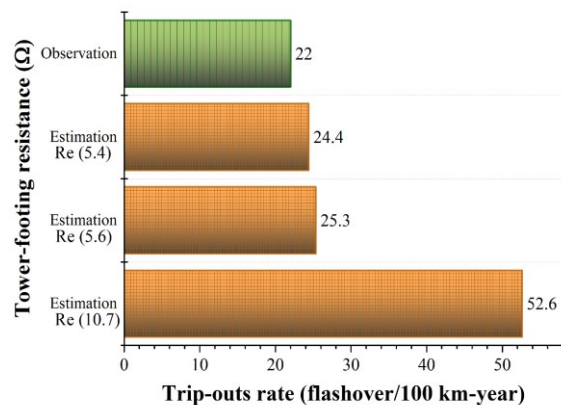
6.1 Trip-out Rates

Figures 11 (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 using tower-footing resistance measured at low frequency because this value can be estimated 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 another case.

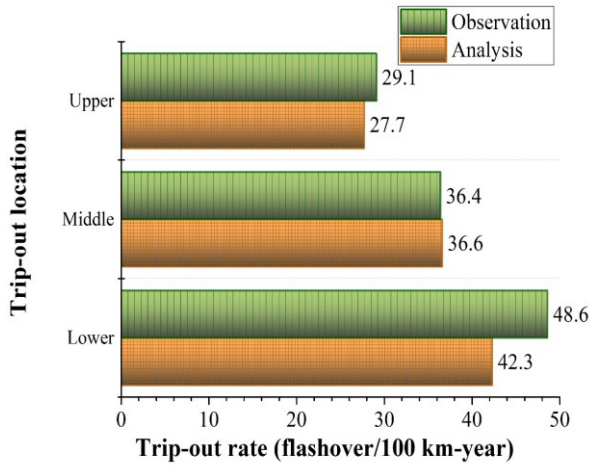


(a). Trip-out rates before improvement of tower-footing resistance.

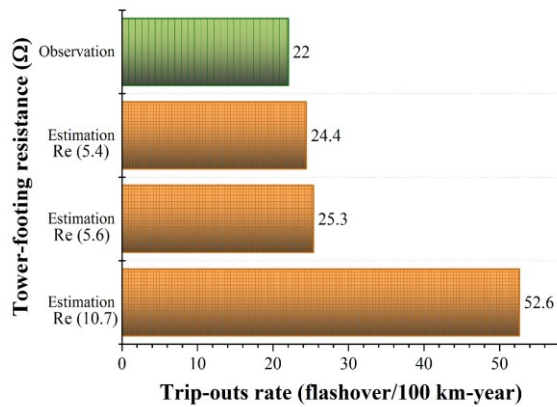


(b). Trip-out rates after improvement of tower-footing resistance.
Fig. 11. Trip-out rates by the IEEE FLASH program with lightning trip-outs observation before (a) and after (b) improvement of tower-footing resistance (Re).

Figures 12 (a) and (b) Shows the dependence of trip-out rates on arm location. The calculated results agree reasonably well with the observation of lightning trip-out rate. From these results, it is shown that the IEEE Flash program and the IEEE method provides reasonable estimates of the trip-out rates for the line under study by taking into consideration the ionizing effect.



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



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

Fig. 12. Dependence of trip-out rates on arm location

7. Conclusion

The results of the lightning trip-out in West Sumatra in Indonesia are presented. It is shown that the main cause of the trip-outs is lightning, which causes 66% of all trip-outs. The main conclusions are as follows:

1. 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.
2. The trip-out rates calculated by taking into 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.

3. 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. This trend can be simulated by the IEEE method using the impulse resistance.
4. The trend that the trip-out ratio becomes high with an increase in 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.
5. 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 of towers No. 1 to 37 towers and on the east side of towers No. 38 to No. 140. In the next area, the thunderstorms often approach the line and the towers from the northeast.
6. The trip-out rate of the line under study can be reduced to less than half of the present rate, 22 flashovers/100 km-year if the tower-footing resistance of all the towers is set to less than 10 Ω and the length of the arcing horn gap is set to more than 1.2 m.

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