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Proposal of analysis method to reduce back-flashover rate taking account of tower footing resistance

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ABSTRACT

The number of lightning stroke on the tower of the 150 kV Koto Panjang-Payakumbuh transmission line located the rocky area has been observed. The high value of tower footing resistance indicates the occurrence of the back-flashover in the transmission line at intensity of 74%. The back-flashover occurrence is dominantly triggered by the tower footing resistance value. Also, the rate of back-flashover has an effect on the value of the tower footing resistance by considering the number of electrode installations. A design is proposed for the grounding system of the tower footings in order to reduce the rate of back-flashover. The results presenting in numerical simulation indicates that it works properly after adding 4 electrodes. That is to say, installing 4 electrodes in each tower has successfully decreased the tower footing resistance value, back-flashovers rate 80% and 90-95% of present value respectively. The insulator voltage can be reduced to less than half of the present voltages as much as 30-50%. In more detail, in tower 77, the value of the tower footing resistance drops to 2.84 Ω, the flashover rate drops to 0.57/100 km/year and the insulator voltage drops to 0.99 MV when a disturbance occurs.

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1. INTRODUCTION

Isokeraunic level (IKL) of the 150 kV Koto Panjang-Payakumbuh transmission line reaches 173 days per year because it is located in a lightning prone area and has a tropical climate [1], [2]. It results in the high number of back-flashover disturbances in the Koto Panjang-Payakumbuh transmission line tower. The back-flashover occurs when a lightning directly strikes the ground wire, which triggers back- flashover due to the overvoltage or overcurrent fails to be grounded [3]–[6]. This study aims to minimize the impulse voltage due to back-flashover on the 150 kV Koto Panjang-Payakumbuh transmission line system and find its main cause [7].

In the electric power system, grounding system is one of the protection systems which manage the disturbance of the overvoltage or the overcurrent in the line. Installing grounding system is expected to be able to protect the line from such disturbances [8]. According to the standard, the effective tower footing resistance value is ≤3 Ω where it is capable to flow current to ground during a fault state [9] as the lightning strike rate from the line is significantly affected by the tower footing resistance [10]–[14].

The investigation data on the Payakumbuh substation transmission from 2017-2021 show 33 of 249 towers have flashovers. Back-flashovers that occurred in the transmission line at rate of 74% were detected by the high value of the tower footing resistance. The high tower footing resistance value itself was influenced by the rock type in the transmission line and the location of the towers, 66% in hilly or mountainous areas [15]–[18].

A counterpoise system is used as the grounding system in the transmission line tower 150 kV Koto Panjang-Payakumbuh and reducing the tower footing resistance value is done by installing the electrode rods horizontally [19], [20]. In general, grounding system with low tower footing resistance will work more effectively. Soil structure is found difference based on its geological properties in each location [21], [22]. The type of soil in the 150 kV Koto Panjang-Payakumbuh transmission line is dominated by rocky soil. The rocky soil is one type of soil that has solid properties and does not have soil mineral content [23], [24]. An analysis of the optimal design for the grounding system of the tower footings is conducted on the 150 kV Koto Panjang-Payakumbuh transmission line in order to obtain a relatively small value of tower footing resistance.

2. METHOD

2.1. Back-flashover

Back-flashover (BFO) is a phenomenon which decreases power transmission lines reliability as well as one of the main factors that trigger the outages in the air line [3], [25]–[27]. Overvoltage or overcurrent due to a lightning stroke on the ground wire that fails to be grounded causes the back-flashover. In this study, the back flashover rate (BFR) analysis was carried out in 38 steps. Flashovers beyond 2 μs are assumed to be infrequent because of the flattening of the volt-time curve [28]. The steps can be illustrated as:

- Determine the flashover isolator voltage at a time of 2 μs (V_t):

$$V_t = 820 \times W \tag{1}$$

where V_t is the insulator flashover strength at 2 μs (kV), W is the insulator length (m).

- Calculate the peak voltage tower per unit $(V_T)_2$ at 2 μs:

$$(V_T)_{2=} \left[Z_I - \frac{Z_W}{1-\psi}\left(1 - \frac{\tau_T}{1-\psi}\right)\right] I \tag{2}$$

where Z_I is the intrinsic circuit impedance, Z_w is the constant wave impedance, ψ is the damping constant that successively reduces the contribution of reflection.

- Calculate the tower flash per 100 km per year:

$$= 0.012 \times IKL \times (b \times 4h'^{1.09}) \times 0.6 \tag{3}$$

- Sum up all values for the total back-flashover rate /100-km/year:

$$BFR = U + M + L + U' + M' + L' \tag{4}$$

where U is the upper, M is the middle, L is the lower.

2.2. Soil resistivity and tower footing resistance

One of the factors that determine the value of tower footing resistance is the soil resistivity. Based on the measurement of the tower footing resistance value, the soil resistivity value can be calculated using formula (5) [29]–[32]. The resistivity values of soil are useful when designing earth-electrode systems.

$$\rho = \frac{2\,\pi\,L\,R}{\left(ln\frac{4L}{a} - 1\right)} \tag{5}$$

Where R is tower footing resistance (Ω), L is length of electrode rod in soil (m), a is electrode rod radius (m). After obtaining the soil resistivity value of the area, calculating the number of the electrode used to improve the tower footing resistance value is done by using the formula (6) [27], [33]–[37]:

$$R_a = \frac{\rho}{2\,\pi\,L}\left(ln\frac{4\,L}{\sqrt[4]{2^{1/2}\,a^3\,r}} - 1\right) \tag{6}$$

where R_a is tower footing resistance (Ω), ρ is soil resistivity (Ωm), L is buried length of electrode (m), a is distance of electrode (m).

2.3. Transient program (EMTP)

EMTP can be projected to analyze transients on circuits containing concentrated parameters (R, L, and C), transmission lines with distributed parameters, and line with no transposition. Phase conductors and shielding cables are modeled based on tower data [26], [38]–[41]. A brief outline of the EMTP-ATP model used purposely for this paper is presented in the form of a model consisting of several components [42]–[45]: i) generator, ii) phase conductors of transmission lines and shielding cables including line termination and power frequency voltage, iii) transmission line tower, iv) tower grounding impedance, v) string insulator (i.e. arcing horn) flashover characteristics, and vi) lightning current and lightning line impedance.

2.4. Investigation data

Figure 1 shows the area of the 150 kV Koto Panjang-Payakumbuh transmission line with a total line length of 86 km. Tower 1-140 is located in area 6 with an IKL of 173 days/year, while the 141-249 tower is located in area 7 and has an IKL of 22 days/year [2]. In this paper, the Back Flashover analysis is carried out on towers that have an IKL of 173 days/year which is found in towers 1-140 [46].

The 150 kV Koto Panjang-Payakumbuh transmission line has four types of tower configurations, namely type AA, BB, CC, and DD. The type of tower used is adjusted to the place and location of the tower planting. Figure 2 shows the configuration of the AA type tower, where 54.5% of the towers with disturbance in the line are using this type. Figure 3 shows the main cause of back-flashover disturbance on the 150 kV Koto Panjang-Payakumbuh transmission line is the tower footing resistance value at rate of 74%.

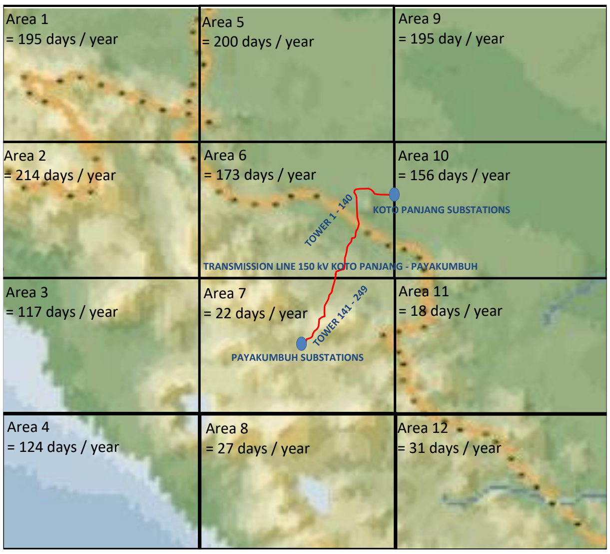

Figure 1. Location of transmission line

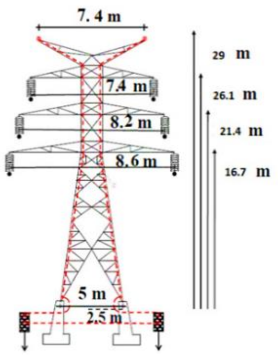

Figure 2. Cconfiguration of the AA type tower

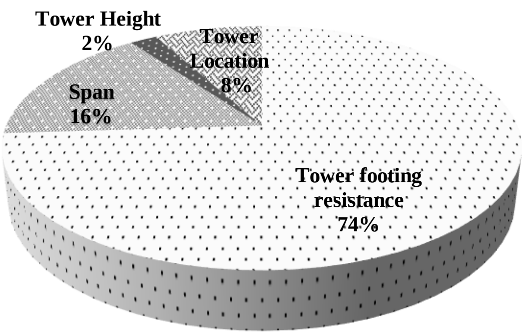

Figure 3. The main cause of back-flashover disturbance

3. RESULTS AND DISCUSSION

Considering those issues found in transmission line, the grounding system was improved by using the formula (8) and (9). Before performing the calculations, 11 towers were classified as having back-flashover disturbance more than twice. By using formula (8) the tower footing resistance value is obtained for each tower as seen in the Table 1. Table 1 shows the results of the tower footing resistance value for towers with the occurrence of back-flashover more than twice. Based on formula (8), the value of soil resistivity is directly proportional to the value of tower footing resistance; in other words, the higher the soil resistivity value, the higher the tower footing resistance value.

Table 1. Tower footing resistance of tower with disturbance

No. Tower	Number of disturbances	Tower footing resistance (Ω)
16	2	6.59
17	2	4.38
54	2	3.44
59	2	5.77
68	2	14.3
70	2	4.4
77	2	16.9
136	2	9.09
50	3	7.5
15	4	7.84
9	5	7

Figure 4 displays the results of the trend line between the data of the tower footing resistance value and the back-flashover disturbance occurrence. It can be seen that the high tower footing resistance has greatly impacted the back-flashover disturbance occurrence. Other factors also can cause the back-flashover such as span length, tower height and tower location. As shown in tower No. 9 with a resistance of 7 ohm, the number of disturbances is 5 times, while in tower No. 77 with a resistance of 16 ohm, the number of disturbances is twice. The length of the span in tower No. 9 is longer than that of No. 77. It can be assumed that the longer the span, the longer the reflected wave will be, so it can increase the voltage on the insulator and cause a higher chance of back- flashover. By using the Anderson method, the back-flashover rate can be calculated as presented in tower No. 77.

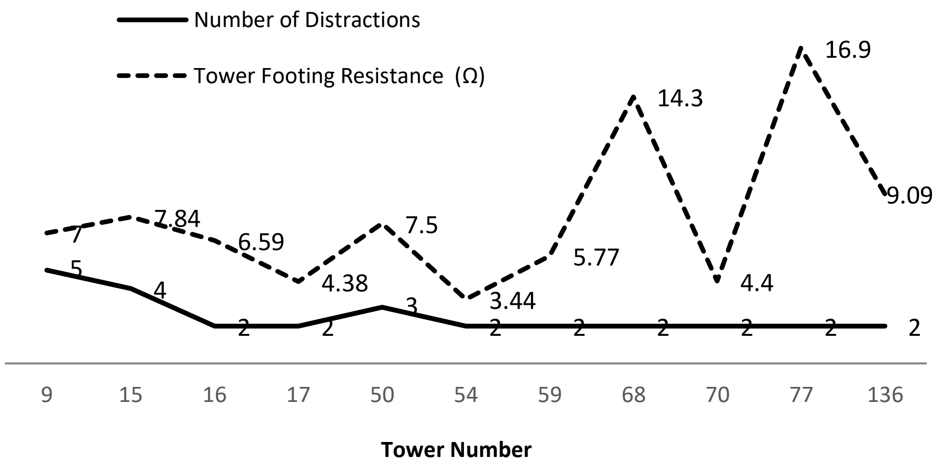

Figure 4. Trend line of tower footing resistance and number of disturbances

Determine the flashover isolator voltage at a time of 2 µs (V_t):

$$V_t = 820 \times 1.36$$
$$V_t = 1.115,2$$

After that determine the travel time range of the tower (τ_t) and the travel time span (τ_s):

$$\tau_t = \frac{30}{300} = 0.1$$
$$\tau_s = \frac{333}{300\times1.36} = 1.23$$

Then, determine the refraction factor of the footing resistance ($\tilde{\alpha}_R$):

$$\tilde{\alpha}_R = \frac{2*16.9}{170+16.9} = 0.181$$

Calculate the peak voltage tower per unit $(V_T)_2$ at 2 µs:

$$(V_T)_2 = \left[76.69 - \frac{56.65}{1-0.081}\left(1 - \frac{0.1}{1-0.081}\right)\right] 1$$
$$(V_T)_2 = 21.8$$

Calculate the tower flash per 100 km per year:

$$= 0.012 \times 173 \times (7 \times 4\,x\,25.74'^{1.09}) \times 0.6$$
$$= 180.5$$

Sum up all values for the total back-flashover rate/100 km/year:

$$BFR = 1.96 + 4.06 + 4.06 + 1.96$$
$$BFR = 12.04$$

After performing calculations using the Anderson method on all towers, the results are obtained as shown in Figure 5.

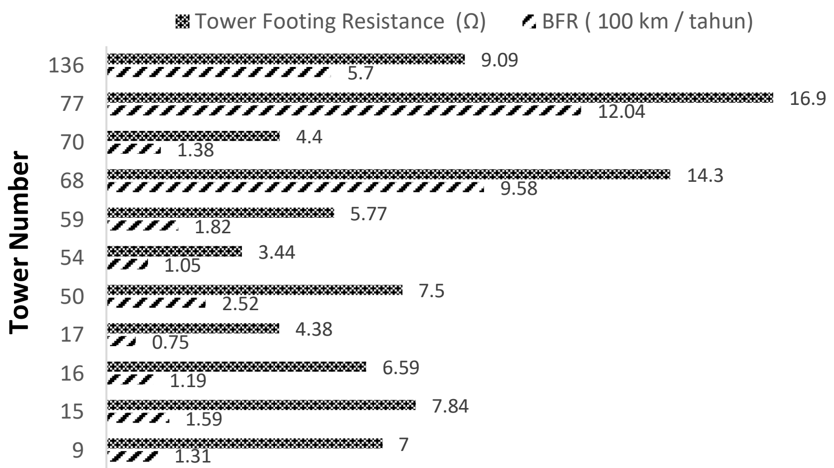

Figure 5. Graph of tower footing value to back-flashover

Figure 5 is a graph of the number of back-flashovers calculated using the Anderson method. This figure shows the higher the tower footing resistance value of a tower, the higher the number of back-flashovers in the tower. After getting the BFO value, an analysis of the peak voltage value of the tower is carried out using EMTP simulation by projecting Heidler as a lightning source with an injection current of up to 100 kA, line circuit cable (LCC) representation as the tower, Line Z as phase wire and RL circuit as an insulator. In the simulation, the value of the generator system voltage used is presented by the normal peak voltage of the system of 150 kV. The simulation circuit is shown in Figure 6.

After obtaining the BFO value, then an analysis of the tower peak voltage value is performed using EMTP simulation by projecting Heidler as a lightning source with an injection current of up to 100 kA, LCC is a representation as tower, line Z projected as phase wire and RL circuit as an insulator. In the simulation, the value of the generator system voltage used is indicated by the normal peak voltage of the system of 150 kV. The simulation circuit can be seen in Figure 6.

Figure 6 is a simulation circuit using EMTP for tower No. 77, by inputting tower data No. 77 in the simulation circuit, the results are as shown in Figures 7 and 8. The voltage wave simulation under normal conditions for the 150 kV Koto Panjang-Payakumbuh transmission line can be seen in Figure 7. Figure 8 presents the simulation results obtained from the XY plot where the red graph shows the magnitude of the R phase insulator voltage of 1.99 MV, the green graph represents the S phase insulator voltage value of 1.1 MV and the blue graph indicates the T phase insulator voltage of 0.55 MV. The results from the simulation show that when a lightning disturbance occurs in the R phase, the insulator voltage in the R phase is higher than the other phases. This is influenced by the coupling factor between the overhead ground wire (OHGW) and the phase conductor, causing the voltage in the R phase is also be greater than in the other phases. Simulation results of all towers with disturbances are as shown in Figure 9.

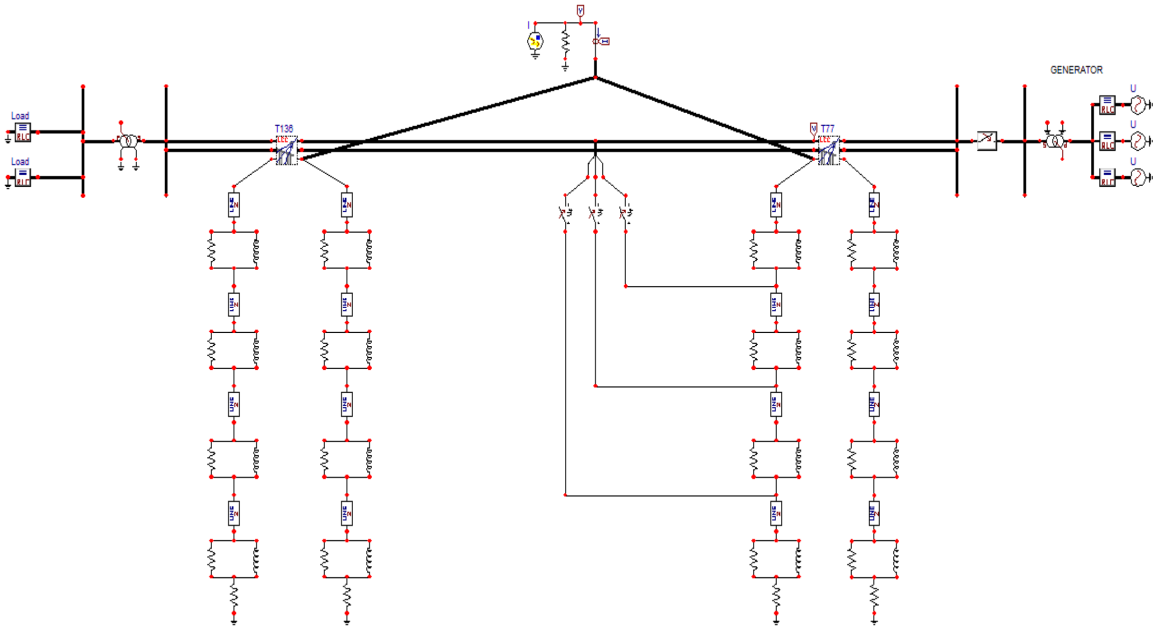

Figure 6. Simulation circuit with EMTP

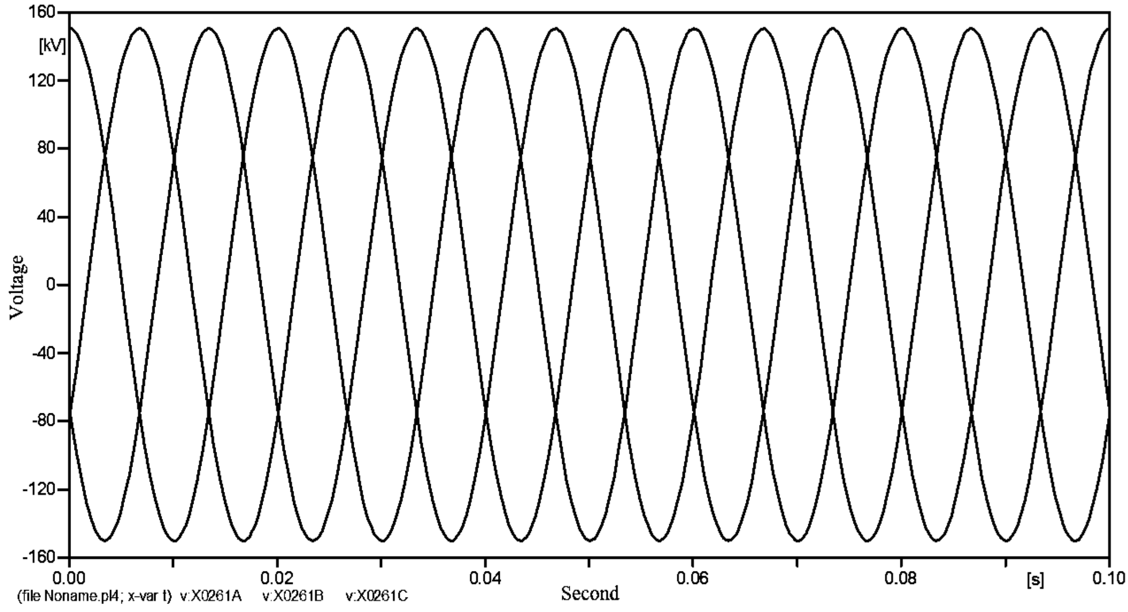

Figure 7. Voltage simulation results in normal conditions

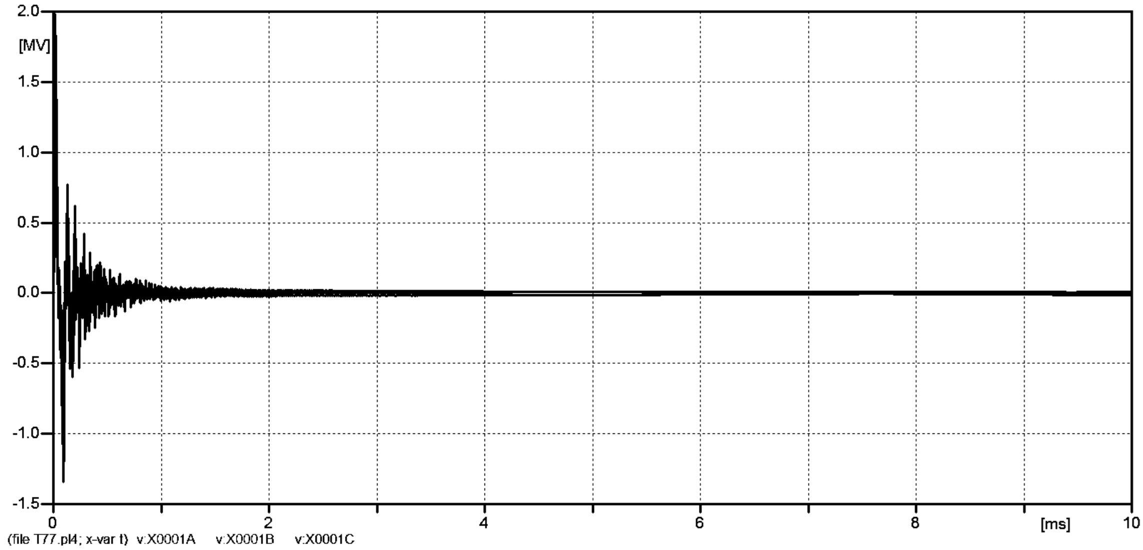

Figure 8. Graph of peak voltage results in tower No. 77

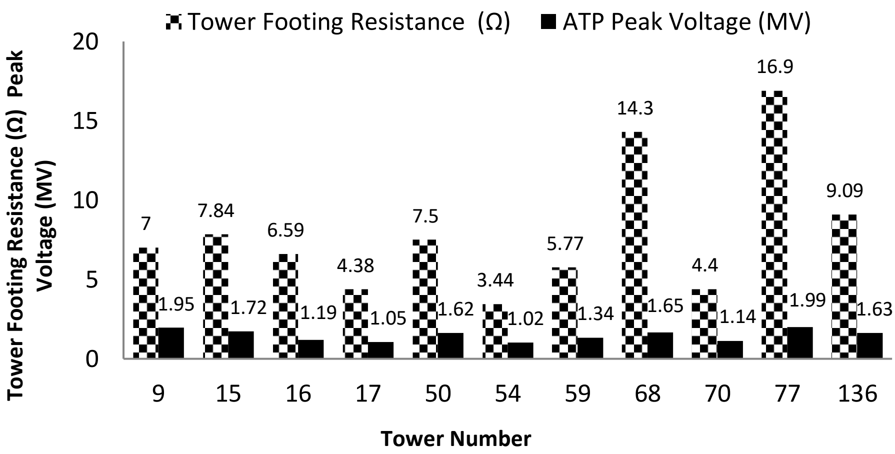

Figure 2. Graph of tower footing resistance to peak voltage tower

Figure 9 indicates that the higher the resistance value, the higher the peak voltage value in the tower. After increasing the number and distance using formula (9) and applying the proposed design for the grounding system in the towers with back-flashover disturbance occurring more than twice. The latest value of the tower footing resistance is obtained and shown in Table 2.

Table 2. Tower footing resistance before improvement

No	No. Tower	Number of Electrodes Before Improvement	The Distance Between the Electrode Rods (m)	Tower footing resistanceR (Ω)
1	9	3	2	7
2	15	3	2	7.84
3	16	3	2	6.59
4	17	3	2	4.38
5	50	3	2	7.5
6	54	3	2	3.44
7	59	3	2	5.77
8	68	3	2	14.3
9	70	3	2	4.4
10	77	3	2	16.9
11	136	3	2	9.09

Table 2 illustrates tower No. 77 with only being installed by 3 rods of electrodes, with the distance among the electrodes at 2 m, and with the tower footing resistance value of 16.90 Ω. After performing some numerical calculations on the addition of the number of electrodes on the 150 kV Koto Panjang-Payakumbuh transmission line, the optimal number of electrodes to obtain a standard resistance value (≤ 3) is 4 electrodes as shown in Figure 10. In the figure it is shown that installing 4 electrodes to the disturbed towers decreases or even meets to the standard number of the resistance value at ≤ 3 Ω. Considering the data presented in Table 2 and Figure 10, the design of the tower foundation grounding system was improved as shown in Figure 11. From Figure 10, 4 electrodes used with a distance of 5 m between the electrodes were more effective in lowering the tower footing resistance value and the back-flashover value.

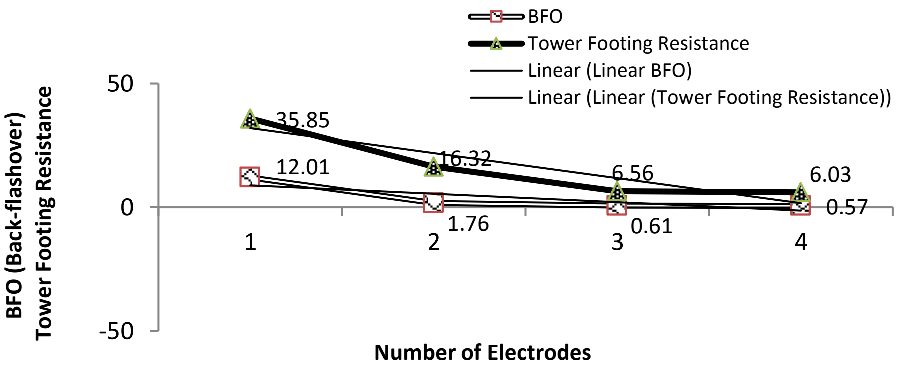

Figure 3. The installing 4 electrodes to the disturbed towers

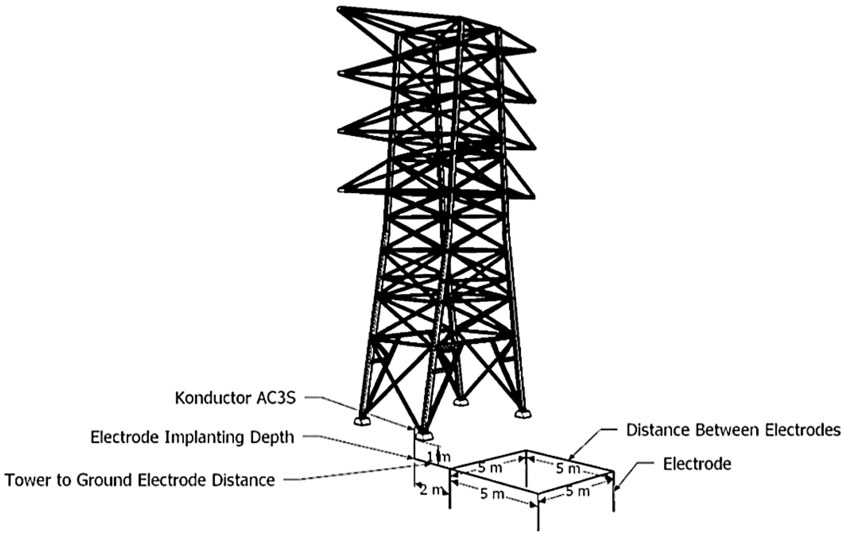

Figure 4. Proposed design of ground system improvement

By using formula (9), the tower footing resistance values in each tower decrease as shown in Table 3. From the results of this numerical calculation, it can be seen that increasing the number and distance of electrodes in the transmission line grounding system can decrease the tower footing resistance values in the transmission line. The results of numerical calculations for tower footing resistance after improvement and the number of back-flashovers can be seen in the Figure 12. The tower footing resistance of tower No. 77 is presented in Figure 12 with the number and distance of the electrodes at 16.90 Ω with a BFO value of 12.04 100 km/year before adding the electrode number and after adding the number of electrodes on the tower the tower footing resistance value decreases to 2.84 Ω so that the BFO value could be reduced to 0.57 100 km/year. The figure also indicates that the lower the resistance value of the tower, the lower the value of the peak voltage as well as it is presented in Figure 13 of the tower simulation No. 77 with the result that shows the decline of the voltage to 1 MV.

Figure 13 shows the simulation results obtained from the XY plot. The red graph is the R phase insulator voltage of 0.99 MV, the green graph is the S phase insulator voltage value of 0.54 MV and the blue graph is the T phase insulator voltage of 0.26 MV. The results of this simulation indicate that the insulator voltage in the R phase reaches the highest voltage during the lightning disturbance. The coupling factor between the OHGW and the phase conductor contribute greatly to this phenomenon and as a result the voltage amount in the R phase is also in the greatest one. Figure 14 also shows a tendency that the higher the tower footing resistance value, the higher the peak voltage value in the tower.

Table 3. Tower footing resistance after improvement

No Tower	Number of Electrodes	The Distance Between the Electrode Rods (m)	Tower footing resistance R (Ω)
9	4	2	1.99
15	4	2	2.23
16	4	2	1.87
17	4	2	1.25
50	4	2	2.13
54	4	2	0.98
59	4	2	1.64
68	4	4	2.81
70	4	2	1.25
77	4	5	2.84
136	4	2	2.58

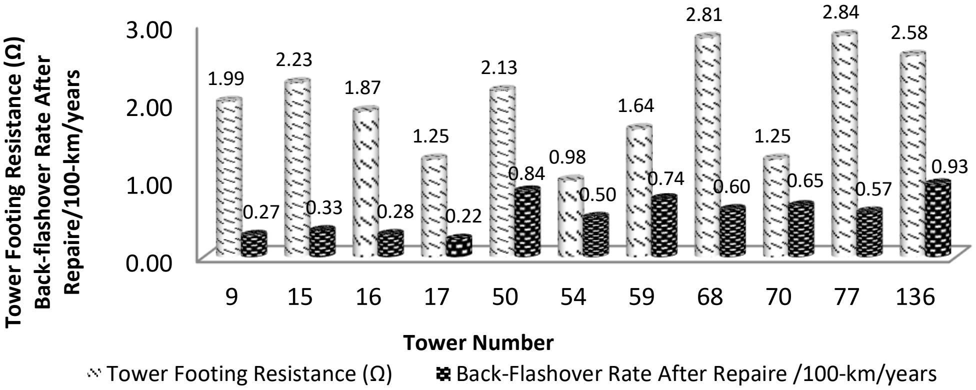

Figure 5. Comparison of back-flashover rate before and after repaire

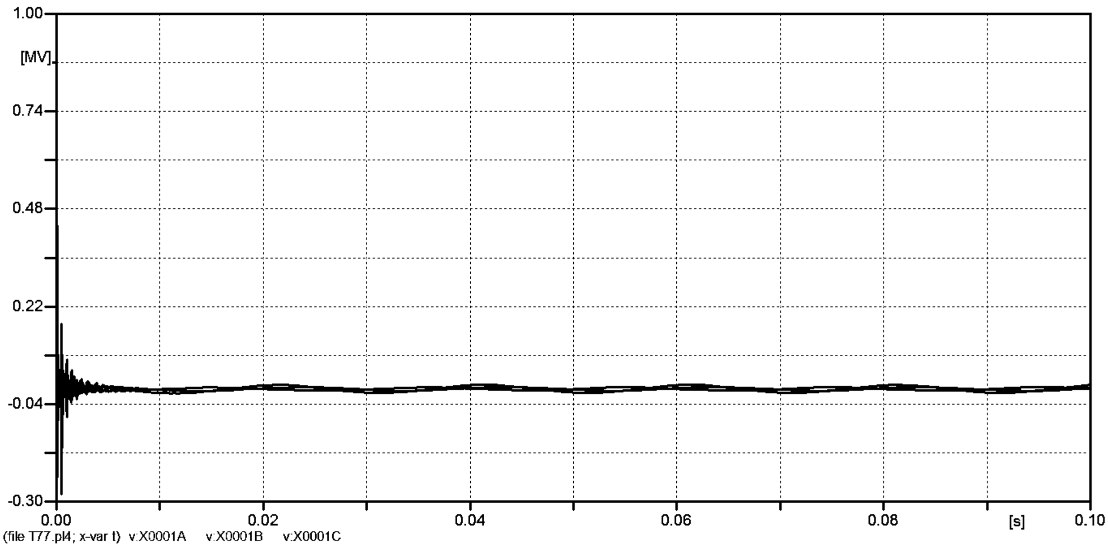

Figure 6. Graph of peak voltage results after repairs to tower No. 77

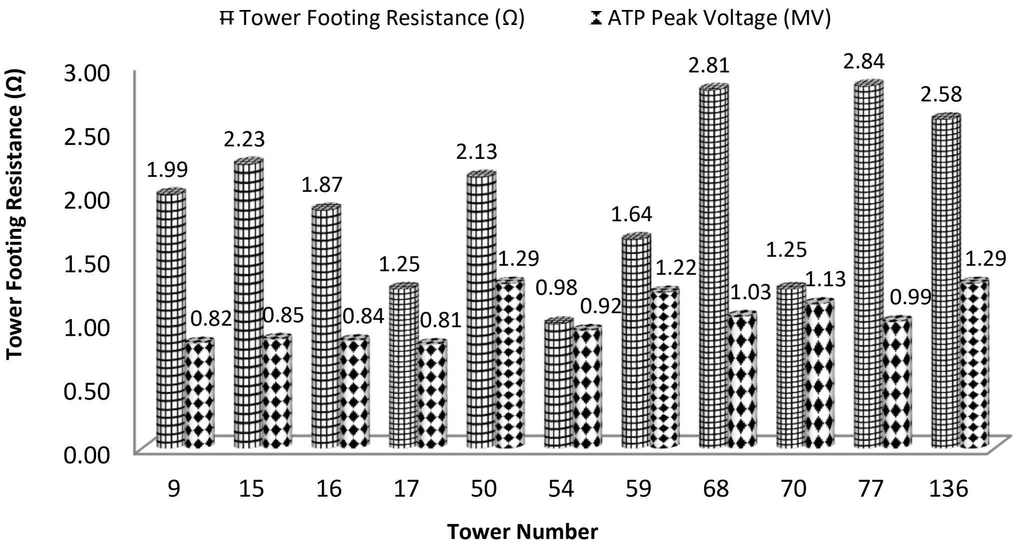

Figure 7. Graph of tower footing resistance to peak voltage tower

4. CONCLUSION

After installing 4 electrodes on the 150 kV transmission line, particularly in towers with back-flashover disturbance and located in rocky areas, it is found that: i) the value of the tower footing resistance in each tower with disturbances drops and can meet the standard value at rate of ≤ 3 Ω; ii) the tower footing resistance value decreases by 80% from the prior one. As shown in tower No. 77, the tower footing resistance value decreases to 2.84 Ω; iii) the back-flashover rate in the transmission line can be reduced to 90% to 95% after the improvement. As illustrated in towers No. 77 and 68. The back-flashover rate decreases to 0.57 and the flashover rate decline to 0.6/100-km/years for each tower; and iv) the insulator voltage drops to 30% to 50% from the prior one during the study. It can be seen in tower No. 77 and 68 with the insulator voltages being 0.9 and 1.03 MV, respectively.

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