International Journal on
Advanced Science
Engineering
Information Technology

Vol.13 (2023) No. 3
ISSN: 2088-5334

An Optimal Design of Grounding System for Tower Footings in Payakumbuh 150 kV Transmission Line of Koto Panjang

Yusreni Warmi [a,*], Zulkarnaini [a], Abdul Rajab [b], Chitra Yuanisa [a], Rizki Oktrinanda Elyas [a],
Andi M Nur Putra [a], Zuriman Anthony [a]

[a] *Department of Electrical Engineering, Institute of Technology Padang, Padang, 25173, Indonesia*
[b] *Department of Electrical Engineering, Andalas University, Padang, 25175, Indonesia*
*Corresponding author: *yusreni@itp.ac.id*

***Abstract*— The 150 kV Koto Panjang – Payakumbuh transmission line has a line length of 86 km with 249 towers, and the occurrence of the back-flashover in their transmission line is 74%, indicated by the high tower footing resistance as that is >3 ohms. The type of rock on the transmission line and the location of the towers, 79% in hilly or mountainous terrains, are among the factors that can cause an increase in the resistance value. The results of this study indicate that the level of back-flashover affects the value of the tower footing resistance by considering the number of electrode installations. When the towers were installed with more electrodes, the value of tower footing resistance, back-flashover level, and insulator voltage could be reduced to less than half of the previous ones. Moreover, the occurrence of the back-flashover rate in each tower can be dropped to ≤ 1 back-flashover rate of 100-km/year. Each tower's soil resistivity value has grown, yet fewer back-flashover disruptions exist. The span's length causes this, as the shorter the span, the faster the reflected wave will travel. As a result, it can lower the voltage in the insulator and diminish the likelihood that a flashover would occur.**

***Keywords*— Grounding system design; tower footing resistance; back-flashover; Anderson method.**

Manuscript received 13 Feb. 2022; revised 19 Nov. 2022; accepted 21 Mar. 2023. Date of publication 30 Jun. 2023.

I. INTRODUCTION

The Koto Panjang–Payakumbuh transmission line is installed in an area with a tropical climate and high risk of lightning prone to an Iso-Ceranic Level (IKL) reaching 173 days per year [1], [2]. The lightning stroke triggers the frequent occurrence of flashover disturbances on the 150 kV Koto Panjang – Payakumbuh transmission line tower. The flashover on the transmission line due to the direct lightning stroke on the protective wire or ground wire is called the Back-flashover phenomenon [3]–[7]. This research helps to find a way to minimize the impulse voltage due to back-flashover on the 150 kV Koto Panjang–Payakumbuh transmission line system by investigating the main cause [8]–[13].

Based on the investigation data on the Payakumbu substation transmission from 2017–2021, 33 towers out of 248 experienced flashovers. The occurrence of the back-flashover was indicated by the high ground resistance value in the transmission line of approximately 74%, and it was due to the type of rock on the transmission line and 79% of the towers located in hilly or mountainous terrains.

The grounding system will immediately secure the line when a disturbance, such as an overvoltage or overcurrent, occurs. The lightning flash that strikes on the line is mainly affected by the tower-footing resistance [10]–[12]. An effectively balanced ground resistance value for a 150 kV transmission line is 3Ω, so the current can manageably flow to the disturbed ground line [11]–[13]. Thus, the yearly weather changes can also affect the grounding resistance.

The grounding system used in the 150 kV transmission line tower Koto Panjang- Payakumbuh currently is a counterpoise system, and the electrode rods are installed horizontally to obtain a relatively low ground resistance value [8], [12]–[15]. That is to say, the lower the soil resistivity level, the more effective it becomes. Each area has a different soil structure based on its geological properties, and rock soil is a type of soil with solid properties and does not contain soil minerals. Therefore, an analysis of the effect of soil resistivity on back Flashover on the 150 kV Koto Panjang–Payakumbuh transmission line tower needs to be carried out to solve those problems.

II. MATERIALS AND METHOD

A. Back-Flashover

Back-Flashover is one of the main factors that cause the outage in the airline as well as a phenomenon that can reduce the reliability of the system on the transmission line [12], [13], [15]–[17]. Back-flashover occurs due to overvoltage or overcurrent when lightning strikes a ground wire that fails to be grounded. In this study, the back-flashover rate analysis was carried out in 38 steps [16], [18], [19]. The following is a description of the calculation steps as follows.
Determine the flashover isolator voltage at a time of 2μs (V_t):

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

Here V_t is the insulator flashover strength at 2 μs in kV, W is the insulator length in meters. The determine the travel time range of the tower (τ_t) and the travel time span (τ_s):

$$\tau_t = \frac{h}{\tau} \tag{2}$$

$$\tau_s = \frac{s}{300 \times 1.36} \tag{3}$$

Here τ_t is the travel time range of the tower in microseconds, h is high of the tower in meters, τ_s the travel time span in a microsecond, s is the tower span length in meters. The determined refraction factor of the footing resistance ($\tilde{\alpha}\_R$):

$$\tilde{\alpha}_R = \frac{2R}{Z_T + R} \tag{4}$$

Here $\tilde{\alpha}_R$ is the refraction factor of the footing resistance, R is the footing resistance in ohm, Z_T is impedansi lonjakan in ohm. Calculate the peak voltage tower per unit $(V_T)_2$ at 2μs:

$$(V_T)_2 = \left[Z_I - \frac{Z_W}{1-\psi}\left(1 - \frac{\tau_T}{1-\psi}\right)\right] I \tag{5}$$

Here $V_{T\text{-}2}$ is the peak voltage tower in kV, Z_I is the intrinsic circuit impedance in ohm, Z_W is a constant wave impedance in ohm, ψ is a damping constant, τ_T is travel time in microseconds. Calculate the tower flash per 100 km per year:

$$= 0.012 \times \text{IKL} \times (b \times 4h'^{1.09}) \times 0.6 \tag{6}$$

Here IKL is isokeraunik level in day/year, b is overhead ground wire separation distance in meter, h' is tower height in meter. Sum up all values for the total back-flashover rate /100-km/year:

$$\text{BFR} = U + M + L + U' + M' + L' \tag{7}$$

B. Soil Resistivity

Soil resistivity is one of the variables that impact how much soil resistance is present. Therefore, the soil resistivity value can be estimated using the formula from the soil resistance measurement [19]–[21]:

$$\rho = \frac{2\pi L R}{\left(ln \frac{4L}{a} - 1\right)} \tag{8}$$

Here ρ is the soil resistivity in ohm meter, L is the length of electrodes in meter, a is the distance between the electrode in meter.

C. Grounding Resistance

The formula below can be used to determine how adding electrodes will affect the soil resistance value [21], [22], [23], [29]:

$$R_a = \frac{\rho}{2\pi L}\left(\ln \frac{4L}{\sqrt[4]{2^{1/2} a^3 r}} - 1\right) \tag{9}$$

Here R_a is grounding resistance in ohm, ρ is the soil resistivity in ohm meter, L is the distance between the electrode in meter, a is the distance between the electrode in meter, r is the electrode radius in meter.

D. Electromagnetic Transients Program (EMTP)

Transients on transmission lines with scattered parameters, lines without transposition, and circuits with concentrated parameters (R, L, and C) can all be analyzed using EMTP. The phase conductors and shielding cables are modeled based on the tower data [10], [23], [24].

A model of multiple parts is utilized to offer a concise summary of the EMTP-ATP model that was specifically employed for this paper [22], [23], [25]–[33]:

- Generator.
- Phase conductors of transmission lines and shielding cables, including line termination and power frequency voltage.
- Transmission line tower, tower grounding impedance.
- String insulator (i.e., arcing horn) flashover characteristics.
- Lightning current and lightning line impedance.

E. Data Collection Method

The data collection methods used in this research were observation, investigation, and literature study. The researchers directly observed objects to be analyzed, such as transmission tower data (grounding resistance, soil resistivity, and lightning disturbance) and Isoceraunic level. Then, interviews were administered to related parties, such as Government Electrical Company staff, to complete the test data. Furthermore, previous journals or studies were analyzed to acquire the standards set as a reference in the analysis and evaluation process. The stages of the research carried out are shown in Fig. 1.

F. Investigation Data

The Koto Panjang-Payakumbuh 150 kV transmission line, which has a total length of 86 km, is depicted in Fig. 2. Tower 1-140 is situated in area 6 and has an IKL of 173 days/year, whereas tower 141-249 is located in area 7 and has an IKL of 22 days/year [2]. Therefore, the Iso Keraunik Level (IKL) of 173 days per year, present in towers 1 through 140, is used in this paper to conduct the Back Flashover analysis [20].

Four different tower layouts exist for the 150 kV Koto Panjang–Payakumbuh transmission line: AA, BB, CC, and DD. The tower type is modified according to the site and position of the tower planting. Fig. 3 shows the arrangement of an AA-type tower, which accounts for 54.5% of all towers with line disruption.

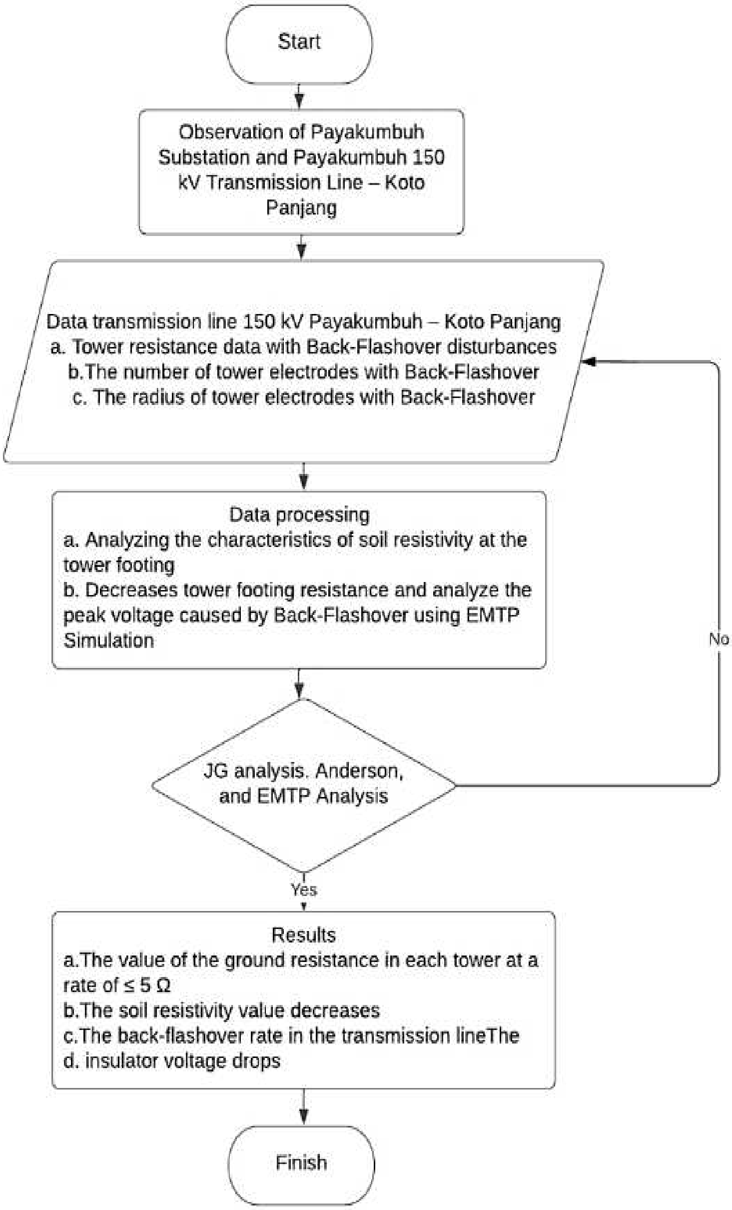


Fig. 1 Research Stages

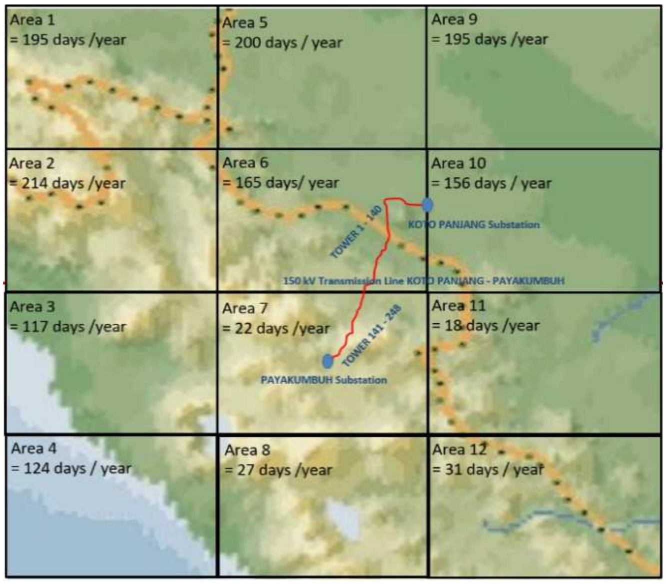
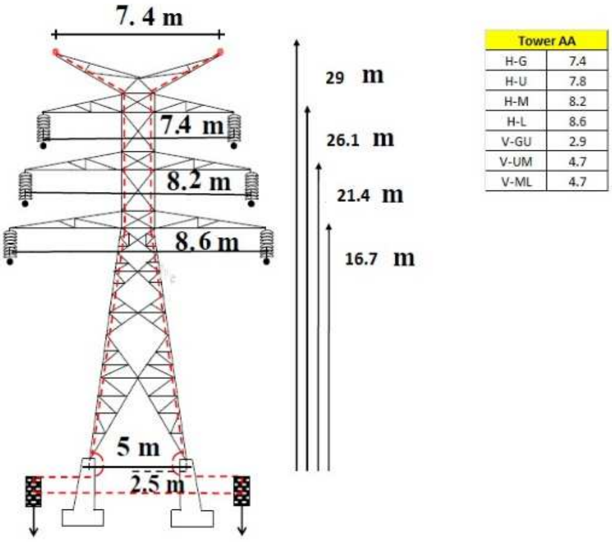


Fig. 2 Location of transmission line



Tower AA	
H-G	7.4
H-U	7.8
H-M	8.2
H-L	8.6
V-GU	2.9
V-UM	4.7
V-ML	4.7

Fig. 3 Configuration of Representative Tower

Pareto data study on the Payakumbuh substation transmission from 2017 to 2021 revealed that 33 towers were impacted by disturbances (trip-out). Table 1 below shows that, after classification, 11 towers had disruptions occur more than twice.

TABLE I
TOWER DATA INVESTIGATION

No Tower	Number Of Disturbances	R (Ω)	Span (m)	Tower Height (m)	Tower Location
8	1	3.85	244	26	Desert
9	5	7	385	26	Hill
13	1	6.5	281	29	Hill
14	1	9.21	204	29	Hill
15	4	2.89	423	26	Hill
16	2	6.59	416	26	Hill
17	2	4.38	221	26	Hill
20	1	6.36	263	38	Hill
36	1	11.9	242	38	Hill
43	1	3	389	26	Hill
48	1	4.59	321	32	Hill
50	3	7.5	278	25	Hill
51	1	4.14	429	38	Hill
54	2	3.44	391	33	Hill
58	1	2.82	431	35	Hill
59	2	5.77	252	35	Hill
60	1	30.5	314	26	Hill
63	1	4.35	427	32	Desert
68	2	14.3	340	29	Hill
70	2	4.4	204	35	Hill
75	1	3.09	359	32	Hill
76	1	6.8	342	35	Hill
77	2	16.9	333	30	Hill
78	1	2.1	224	26	Hill
82	1	2.56	419	29	Hill
89	1	15.41	397	38	Desert
98	1	2.17	281	36	Desert
113	1	9.12	362	32	Hill
132	1	8.71	329	38	Desert
133	1	5.61	223	38	Desert
134	1	7	429	29	Hill
135	1	6.54	428	41	Desert
136	2	9.09	345	35	Desert

Table 1 is data of towers that have undergone back-flashover. The table indicates that the soil resistance value, span length, tower height, and tower area position often cause the back-flashover on the 150 kV Koto Panjang - Payakumbuh transmission line.

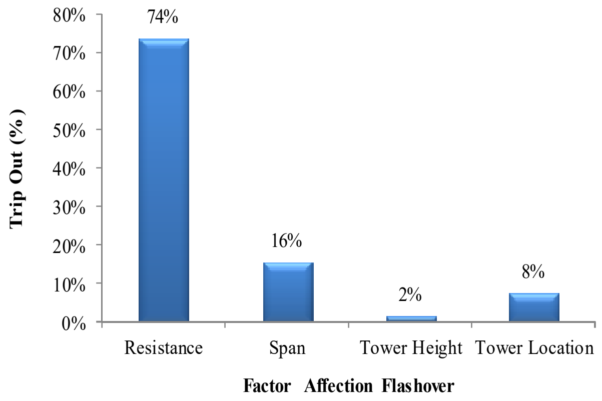


Fig. 4 Factors Affection Flashover

According to Fig. 4, the resistance value at a rate of 74% is the primary contributor to the back-flashover disturbance on the 150 kV Koto Panjang-Payakumbuh transmission line.

III. RESULT AND DISCUSSION

The grounding system was enhanced by applying the formula (8) - considering the transmission line problems (9). 11 towers were identified as having more than double the average amount of back-flashover disturbance before the calculations were done. Therefore, the soil resistivity value for each tower is calculated using formula (8), as shown in the table below.

TABLE II
SOIL RESISTIVITY OF TOWER WITH DISTURBANCE

No. Tower	Number of distractions	Resistance (Ω)	Soil Resistivity (Ω.m)
16	2	6.59	13.98
17	2	4.38	9.29
54	2	3.44	7.3
59	2	5.77	12.24
68	2	14.3	30.34
70	2	4.4	9.33
77	2	16.9	35.85
136	2	9.09	19.28
50	3	7.5	15.91
15	4	7.84	16.63
9	5	7	14.85

Table II shows the results of the soil resistivity value for towers with the occurrence of back-flashover more than twice. Based on the formula (8) the value of soil resistance is directly proportional to the value of soil resistivity; in other words, the higher the value of the soil resistance, the higher the value of the soil resistivity.

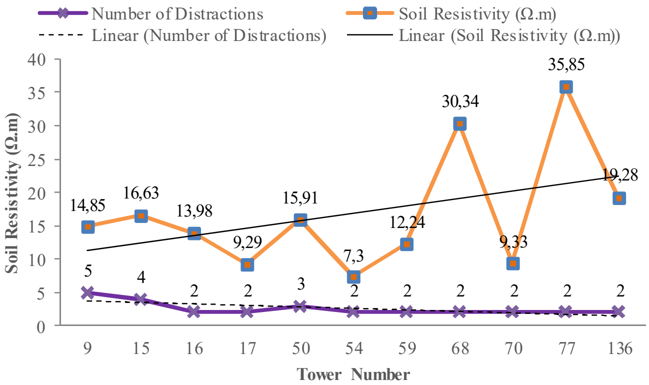


Fig. 5 Trend Line of Soil Resistivity and Number of Disturbances

Fig. 5 displays the trend line results between the soil resistivity value data and the back-flashover disturbance occurrence. It can be seen that the high soil resistivity 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 soil resistivity of 14.85 Ω.m, the number of disturbances is five times, while in tower No. 77, with a resistivity of 35.85 Ω.m, the number of disturbances is twice. 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.

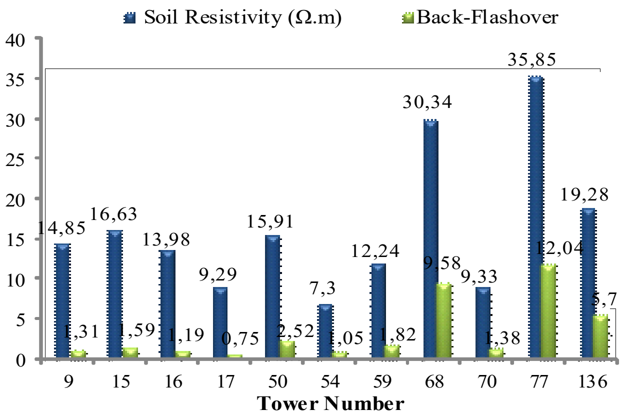


Fig. 6 Graph of Soil Resistivity Value to Back Flashover

Fig. 6 is a graph of the back-flashover value calculated using [25]–[27], so the back-flashover rate value is obtained for the trip-out tower. This figure shows that the higher the soil resistivity value of a tower, the higher the Back-flashover value on the tower. After obtaining the back-flashover rate value, then an analysis of the tower peak voltage value is performed using EMTP simulation [19], [28]–[31] by projecting Heidler as a lightning source with an injection current of up to 100 kA, Line Circuit Cable (LCC) is a representation as the 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 Fig.7 below.

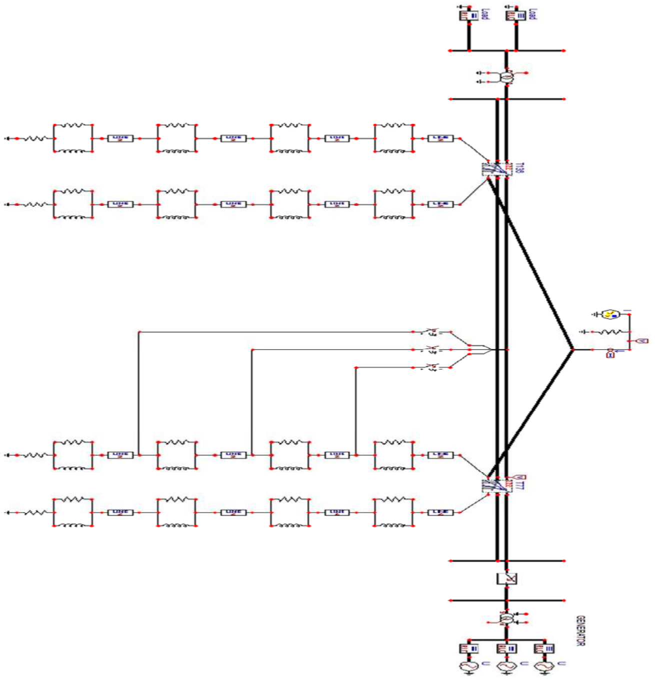


Fig. 7 Simulation Circuit with EMTP

Fig. 7 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 Fig. 8 and Fig. 9. The voltage wave simulation under normal conditions for the 150 kV Koto Panjang - Payakumbuh transmission line can be seen in Fig. 8.

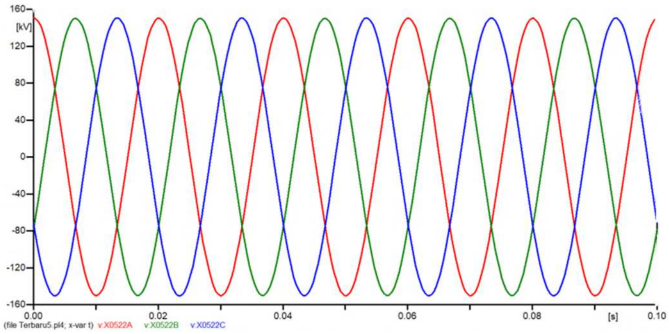


Fig. 8 Voltage Simulation Results in Normal Conditions

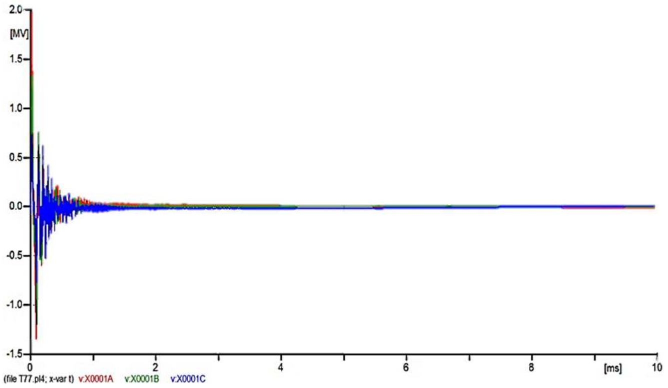


Fig. 9 Graph of Peak Voltage Results in Tower 77

Fig. 9 shows the simulation results obtained from the XY plot are a red graph showing the magnitude of the R phase insulator voltage of 1.99 MV, a green graph for the S phase insulator voltage value of 1.1 MV, and a blue graph for the T phase insulator voltage is 0.55 MV. The simulation shows that when a lightning disturbance occurs in the R phase, the insulator voltage in the R phase is the highest voltage of the other phases. This is due to the coupling factor between the overhead ground wire (OHGW) and the phase conductor, causing the voltage in the R phase to be greater than in the other phases. In this condition, the cause of the voltage spike can be identified by applying Ohm's law, where current and voltage are directly proportional. If the current is greater, the voltage will also be large, and vice versa. Simulation results of all towers with disturbances are shown in Fig. 10 below.

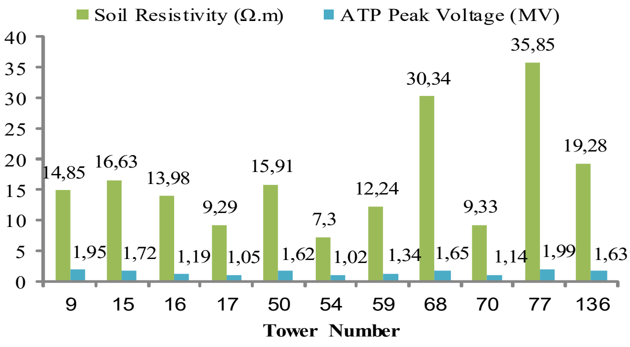


Fig. 10 Graph of Soil Resistivity to Peak Voltage Tower

In Figure 10, it can be seen that the higher the soil resistivity value, the higher the peak voltage value in the tower. Improving soil resistance by having more electrodes and formulating it with the formula (9) – (11) for towers that have tripped out more than two times can obtain the latest resistivity values, as shown in the table below.

TABLE III
SOIL RESISTIVITY BEFORE IMPROVEMENT

No Tower	Number of Electrodes	The Distance Between the Electrode Rods (m)	R (Ω)	ρ (Ω.m)
9	3	2	7.00	14.9
15	3	2	7.84	16.6
16	3	2	6.59	14.0
17	3	2	4.38	9.3
50	3	2	7.50	15.9
54	3	2	3.44	7.3
59	3	2	5.77	12.2
68	3	2	14.30	30.3
70	3	2	4.40	9.3
77	3	2	16.90	35.9
136	3	2	9.09	19.3

Table 3 illustrates tower number 77 with resistivity before improvement with the a soil resistivity value of 35.85 Ω.m and the number of electrodes of only 3 rods and after adding the number of electrodes to 11 rods, it is calculated with the formula (9)-(11), as a result, soil resistivity in the tower decreases to 6.07 Ω.m. From the results of this numerical calculation, it can be seen that increasing the number of electrodes in the transmission line grounding system can reduce the soil resistivity value in the transmission line. The results of numerical calculations for resistivity after repair and the number of back-flashovers can be shown in the graph below:

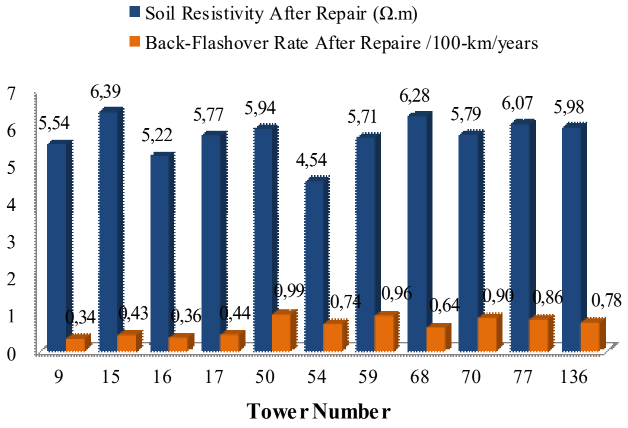


Fig. 11 Comparison of back-flashover Rate before and after repair

Fig. 11 illustrates tower No. 77 with a soil resistivity value of 35.85 Ω.m and a back-flashover value of 12.04 100 km/year, and after adding the number of electrodes, the soil resistivity value decreases to 6.07 Ω.m so that the back-flashover value can be reduced to 0.86 100 km/year. Fig. 12 shows that when the tower's soil resistivity decreases, the tower's peak voltage value will also decrease, as shown in the simulation of tower 77 with the result that the voltage drops almost reaching 1 MV.

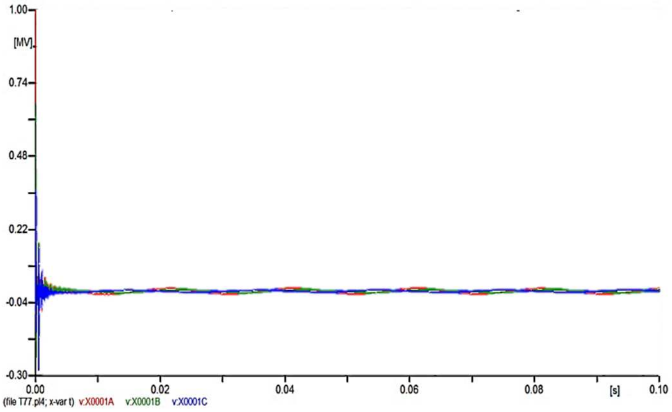


Fig.2 Graph of Peak Voltage Results after repairs to Tower 77

Fig. 12 presents the simulation results from the XY plot where the magnitude of the R phase insulator voltage of 0.99 MV is the red graph, the S phase insulator voltage value of 0.54 MV is the green graph, and the T phase insulator voltage is 0.26 MV is the blue graph. It indicates that the insulator voltage in the R phase reaches the highest voltage than the other phases when there is a lightning disturbance in the R phase. The coupling factor between the overhead ground wire (OHGW) and the phase conductor is the main culprit for this incidence, where it triggers greater voltage in the R phase than in the other phases.

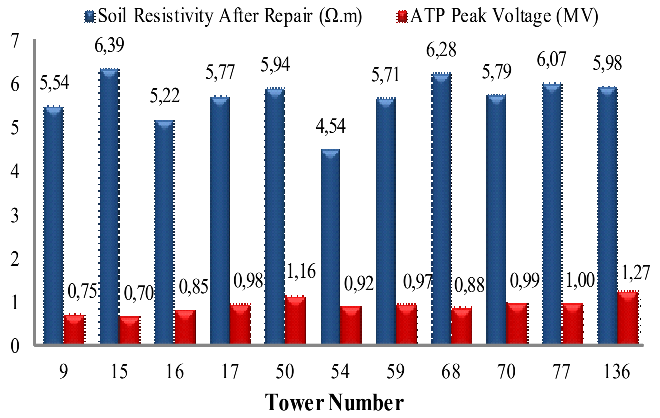


Fig. 3 Graph of Soil Resistivity to Peak Voltage Tower

IV. CONCLUSION

Based on the investigation of the number of back-flashover disturbances in the 150 kV transmission line, especially in towers located in rocky areas, it can be concluded as follows; the number of back-flashover disturbances tends to be influenced by 74% of the soil resistance value in the rocky areas. This indicates that the high soil resistance is caused by soil resistivity. The number of the grounding electrode is increased to obtain the ground resistance value to be 3 ohms. The highest number of electrodes is in tower 77, which is 11 rods because this tower has a high ground resistance value before the repair.

When each tower is installed with more electrodes, the tower footing resistance, the soil resistivity value, back-flashover level, and insulator voltage in the studied line can be reduced to less than half of their respective previous values. This can be seen in tower 77, where the tower footing resistance reduces to 0.99, the soil resistivity value drops to 6.07 Ω.m, the back-flashover rate decreases to 0.86 flashover rate/km/years, the insulator voltage decline to 0.9 MV when the disturbances occur. Another factor affecting the number of back-flashovers in the lines is the span length; this can be seen in towers 68 and 77.

The soil resistivity value in each tower has increased, but the number of back-flashover disturbances is lower. This is due to the length of the span because the shorter the span, the faster the reflected wave will be; consequently, it can reduce the voltage in the insulator and minimize the chance of flashover occurrence.

ACKNOWLEDGMENT

The authors acknowledge the support of a Grant from the Directorate General of Higher Education (DGHE) of Indonesia Number: 162/E5/PG.02.00.PT/2022, 024/LL10/PG.AK/2022.

REFERENCES

[1] The Distribution and Load Control Center Sumatera (Sumatera P3B), “Lightning Density,” Monthly Report, Sumatera P3B, Indonesia, 2013.

[2] Meteorological and Geophysical of Padang Panjang, “Annual Report,” BMKG Padang Panjang, Indonesia, 2017.

[3] N. Malcolm and R. K. Aggarwal, “An analysis of reducing back flashover faults with surge arresters on 69/138 kV double circuit transmission lines due to direct lightning strikes on the shield wires,” *12th IET Int. Conf. Dev. Power Syst. Prot. DPSP 2014*, pp. 1–6, 2014.

[4] M. Asadpourahmadchali, M. Niasati, and Y. Alinejad-Beromi, “Improving tower grounding vs. insulation level to obtain the desired back-flashover rate for HV transmission lines,” *Int. J. Electr. Power Energy Syst.*, vol. 123, no. February, p. 106171, 2020, doi: 10.1016/j.ijepes.2020.106171.

[5] J. He, X. Wang, Z. Yu, and R. Zeng, “Statistical analysis on lightning performance of transmission lines in several regions of China,” *IEEE Trans. Power Deliv.*, vol. 30, no. 3, pp. 1543–1551, 2015, doi: 10.1109/TPWRD.2014.2363122.

[6] R. de la Rosa, G. Enriquez, and J. L. Bonilla, “Contributions to lightning research for transmission line compaction,” *IEEE Trans. Power Deliv.*, vol. 3, no. 2, pp. 716–723, 1988, doi: 10.1109/61.4310.

[7] PLN, “Earthing at Substations and Transmission Networks,” no. 0053, 2020.

[8] Y. Warmi and K. Michishita, “Lightning trip-out of 150 kV transmission line: A case study,” *Int. Rev. Electr. Eng.*, vol. 12, no. 3, pp. 260–266, 2017, doi: 10.15866/iree.v12i3.12233.

[9] Y. Warmi and K. Michishita, “Tower-footing resistance and lightning trip-outs of 150 kV transmission lines in west sumatra in Indonesia,” *MATEC Web Conf.*, vol. 215, pp. 4–11, 2018, doi: 10.1051/matecconf/201821501022.

[10] P. Das and A. Baral, “Effect of Tower Footing Resistance on Back Flashover for A Double Circuit Line,” *2019 8th Int. Conf. Power Syst. Transit. Towar. Sustain. Smart Flex. Grids, ICPS 2019*, pp. 1–6, 2019, doi: 10.1109/ICPS48983.2019.9067355.

[11] Y. Warmi, “Horn Length Estimation for Decrease of Tripout Rates on 150 kV Transmission Lines in West Sumatra in Indonesia,” pp. 1–6, 2018.

[12] Y. Warmi and K. Michishita, “Improvement of Lightning Protection Design of 150 kV Transmission Lines in West Sumatra in Indonesia,” *Int. Colloq. Light. Power Syst.*, p. 9, 2017.

[13] Y. Warmi and K. Michishita, “A Study on Lightning Outages on the 150 Kv Transmission Line of Payakumbuh – Koto Panjang in West Sumatra in Indonesia,” *19th Int. Symp. High Volt. Eng.*, pp. 23–28, 2015.

[14] Y. Warmi and K. Michishita, “Investigation of lightning tripouts on 150-kV transmission lines in West Sumatra in Indonesia,” IEEJ Trans. Electr. Electron. Eng., vol. 11, no. 5, pp. 671–673, 2016, doi: 10.1002/tee.22286.

[15] Y. Warmi, S. Amalia, Z. Antony, and F. R. Yanti, “Experimental Investigation of Insulator Dielectric Strength of Transmission Tower in Rocky Areas,” vol. 12, no. 1, pp. 2–8, 2022

[16] Y. Warmi, Zulkarnaini, and Abdul Rajab “Proposal of analysis method to reduce back-flashover rate taking account of tower footing resistance,” IJECE vol. 5, no. 1, pp. 94–106, 2023, doi: 10.1591/ijece.v13i1.

[17] J. He, R. Zeng, S. Chen, S. Li, and W. Wu, “Impulse characteristics of grounding systems of transmission-line towers in the regions with high soil resistivity,” *POWERCON 1998 - 1998 Int. Conf. Power Syst. Technol. Proc.*, vol. 1, pp. 156–162, 1998, doi: 10.1109/ICPST.1998.728944.

[18] M. Kizhlo and A. Kanbergs, “Research of the parameter changes of the grounding system,” *WNWEC 2009 - 2009 World Non-Grid-Connected Wind Power Energy Conf.*, pp. 8–11, 2009, doi: 10.1109/WNWEC.2009.5335821.

[19] W. M.Telford, L. P. Geldart, and R. E. Sheriff, *Applied Geophisics*, 2nd ed. Cambridge: Cambridge University Press, 1990.

[20] S. Visacro and F. H. Silveira, “The Impact of the Frequency Dependence of Soil Parameters on the Lightning Performance of Transmission Lines,” *IEEE Trans. Electromagn. Compat.*, vol. 57, no. 3, pp. 434–441, 2015, doi: 10.1109/TEMC.2014.2384029.

[21] D. Stanchev, “Model study of lightning overvoltages in substation due to back flashover of overhead transmission line 220 kv,” *2018 10th Electr. Eng. Fac. Conf. BulEF 2018*, pp. 1–4, 2019, doi: 10.1109/BULEF.2018.8646928.

[22] J. Anderson, “Lightning Performance of Transmission Lines.” Electric Power Research Institute, California, pp. 545–597, 1982.

[23] T. S Hutahuruk, *Power System Neutral Earth And Equipment Earth*. Jakarta, Indonesia: Erlangga, 1987.

[24] J. L. Manager and N. B. Member, “Simplified two layer model substation ground grid design methodology,” *IEEE Trans. Power Deliv.*, vol. 5, no. 4, pp. 1741–1750, 1990, doi: 10.1109/61.103669.

[25] IEEE Power and Energy Society - Substations Committee, *IEEE Std. 81- Guide for Measuring Earth Resistivity , Ground Impedance , and Earth Surface Potentials of a Grounding System IEEE Power and Energy Society*, vol. 2012, no. December. 2012.

[26] H. B. Dwight, “Calculation of Resistances to Ground,” *Trans. Am. Inst. Electr. Eng.*, vol. 55, no. 12, pp. 1319–1328, 1936, doi: 10.1109/T-AIEE.1936.5057209.

[27] Y. L. Chow, M. M. Elsherbiny, and M. M. A. Salama, “Resistance formulas of grounding systems in two-layer earth,” *IEEE Trans. Power Deliv.*, vol. 11, no. 3, pp. 1330–1334, 1996, doi: 10.1109/61.517487.

[28] X. Cao, G. Wu, W. Zhou, and R. Li, “New method for calculating ground resistance of grounding grids buried in horizon two-layer soil,” *2008 Int. Conf. High Volt. Eng. Appl. ICHVE 2008*, pp. 241–244, 2008, doi: 10.1109/ICHVE.2008.4773918.

[29] M. El Sherbiny, “Simple formulas for calculating the grounding resistance of rodbed buried in non-uniform soil,” *Midwest Symp. Circuits Syst.*, vol. 2, no. 1, pp. 1281–1284, 1994, doi: 10.1109/mwscas.1994.519043.

[30] S. Hardi, F. Mirza, F. R. A. Bukit, and Rohana, “Influence of Lightning Characteristics on Back Flashover in Extra High Voltage Transmission Line: A case study,” *J. Phys. Conf. Ser.*, vol. 1811, pp. 1–9, 2021, doi: 10.1088/1742-6596/1811/1/012048.

[31] S. Astinfeshan, A. Gholami, and M. Mohajeri, “Analysis of corona effect on lightning performance of HV overhead transmission line using ATP/EMTP,” *ICEE 2012 - 20th Iran. Conf. Electr. Eng.*, no. Icee20 12, pp. 485–488, 2012, doi: 10.1109/IranianCEE.2012.6292406.

[32] P. Sarajcev, J. Vasilj, and D. Jakus, “Method for estimating backflashover rates on HV transmission lines based on EMTP-ATP and curve of limiting parameters,” *Int. J. Electr. Power Energy Syst.*, vol. 78, pp. 127–137, 2016, doi: 10.1016/j.ijepes.2015.11.088.

[33] Cigré WG C4.501, *Guideline for Numerical Electromagnetic Analysis Method and its Application to Surge Phenomena*, no. June. 2013.