

RESEARCH ARTICLE

High Voltage Insulation Assessment Based on a Mathematical Model of Transmission Line with Lightning Strike Simulation

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Abstract

Lightning is a natural source that causes a major failure on power system especially in transmission line. It could decrease the reliability of the power system due to generating the overvoltage phenomenon which lead to insulator broken. When lightning strokes the tower or the ground wire, the effect of different lightning will have different consequences for voltage rise and affect to discharge process. During the discharge process, the voltage in each arm of tower will rise and lead to insulator being broken due to insulator being unable to withstand the current surge. Hence, the number of footing resistance took a crucial part during this process. Higher footing resistance will hinder the discharge process and affect the magnitude of voltage raises throughout the transmission lines. In PT. Vale Indonesia, the magnitude of footing resistance is varied and no standardized value to maintain the footing resistance value. The standardization of footing resistance is required to prevent large-scale failure from occurring in the system. This paper aimed to obtain the effect of direct strike in transmission tower and the optimum value of footing resistance to prevent large scale of failure that affect to production for PT. Vale Indonesia transmission line system considered by simulation from ATPDraw.

Keywords: footing resistance, insulation coordination, lightning strikes, overvoltage, transmission lines

I. INTRODUCTION

In worldwide, the probability of permanent failure in power system caused by lightning stroke on transmission line (TL) could reach 5-10% [1]. Due to PT. Vale Indonesia is located near the equator with high humidity and has high isokeraunic level transmission line system failures occurred repetitively. The soil itself develops from ultrabasic rocks, which means the soils contain a high concentration of nickel (Ni), chromium (Cr), and other heavy metals. It leads to the high probability of high intensity lightning surges occurring throughout the area. It proved by historical failure leads to power interruption from 2015-2023, failure due to lightning stroke is 32%. According to those data [2], PT. Vale Indonesia suffered huge loss production.

High intensity lightning strike will affect the performance of TL. The lightning strike has made an immense contribution to elaborate overvoltage phenomenon and classified as an external cause. The lightning strike is divided into two terms, direct and indirect strike. Indirect stroke is developing induced charge on the line as a result of lightning strokes close to ground. For direct strike, the lightning current directly hits the tower for the cloud and leads to voltage to increase rapidly in contact point. The contact point could be overhead ground wire (OHGW) or the conductor itself. When lightning hits the OHGW, the current will discharge through the tower. In this circumstance, the footing resistance (FR) shall be as low as possible to optimize current discharge [3]. Otherwise, if the footing resistance is high, the probability of the lightning current will return to the tower is high. It could be assumed that the system

fails. Once the system fails to discharge current, it could lead to flash-over over the tower, insulator, or one or more phase conductors [4]. In [5], high footing resistance will increase the lightning overvoltage in the insulator string by 24%. Using IEC lightning wave characteristics, it was found that by increasing the footing resistance, it could cause flashover [6]. It also influences by characteristics of the lightning wave [7], [8]. To mitigate the impact of lightning strikes, a study related to overvoltage in TL is required. This study is used to obtain and define the insulation ability towards voltage stress [9], and basic insulation level (BIL) of equipment towards overvoltage phenomenon.

This study aims to evaluate and improve PT. Vale Indonesia transmission line system against the current surge magnitude of direct strike, the comparison between long period lightning waveform for the transmission line system, and the impact of the footing resistance to voltage rise in the ultrabasic rocks area. The modelling of the surge impedance of tower using multi-story [10] approach and analysis were conducted by EMTP-ATP. Moreover, lightning current characteristics used in this simulation refer to IEC standard [1] and [11]. This simulation carried out by considering the actual parameters from PT. Vale Indonesia transmission line data parameters. The presented form of analysis contributed to the over-voltage and insulation coordination studies for system security of PT. Vale Indonesia.

II. METHODS

Overvoltage analysis is mandatory power system analysis to ensure the sustainability and reliability of power system, especially in transmission line system. In Fig. 1, it was explained that the process methodology of this research. The data were obtained by actual maintenance data, specification of insulator data, and tower structure data. This data will be used in multi-story modelling system. For overvoltage analysis, the surge current will apply into the highest elevation tower along the transmission line. The system will test with various magnitude and wave characteristics of lightning current to obtain the overvoltage characteristics along the transmission line during the strokes. Furthermore, the simulation also considered various footing resistance to find the impact of high footing resistance in the transmission line.

A. Lightning Impulse Current

A lightning strike is a sudden movement of electric charge causing flow of impulse current. This phenomenon similar with breakdown of insulating properties in very long gap distance. The configuration of the system is explained by Fig.2, the impulse was given in electrode positive plane, or it this case stand for cloud. The very long gap is air along the cloud and ground. The air act as an insulation. Due to lightning carried out high surge current, the electric field intensity was developed below the plane and above the rod. Partial breakdown (PB) [12] begins at the location with high field intensities and generates free charge. The free charge or the current always follows the least resistance path in air and follow the least resistance path.

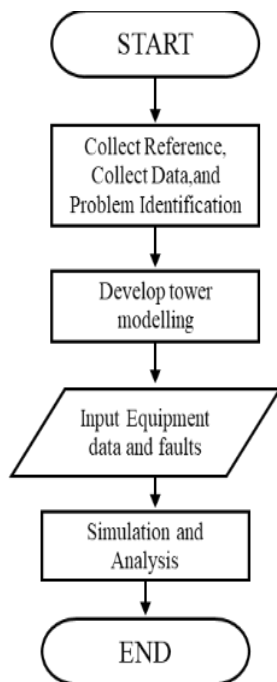


Fig. 1 Flow-chart of overvoltage study

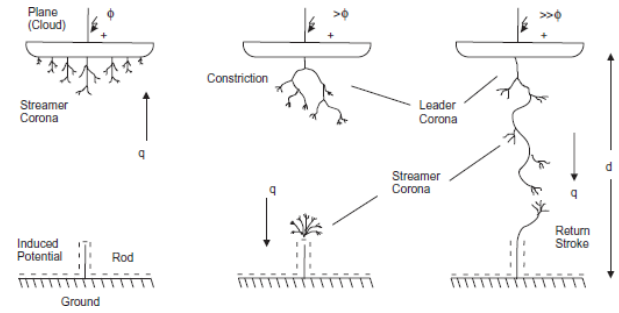


Fig. 2 Schematic of the development of the breakdown in long gap insulation properties [12]

The lightning is one of the impulse waves, the waveform itself contains the front wave T_1 or t_f and the tail wave T_2 or t_r . The characteristic of front wave is steep shape, rapid rise, and high rate of change whereas the tail has slower decay, gentle slope, and lower rate of change [13]. In following figure was explain that T_1 or t_f is time to takes the voltage to rise from 10 to 90% of its peak value. Furthermore, the longer decay time or T_2 or t_r is time to decay from its peak value to 50% of its peak value.

The lightning waveform characteristic was explained by several standard [14]. The IEC standard is commonly used to approximate the effect of lightning discharges. The lightning impulse current according to IEC is $1.2/50\mu s$ [15]. It means that the front wave has values $1.2\mu s$ and the tail has values $50\mu s$. In following table, it was explained that several waveform lightning characteristics also considered.

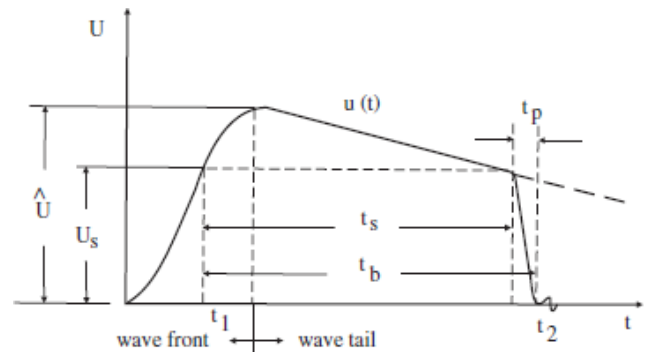


Fig. 3 The lightning waveform characteristic[12]

TABLE 1. THE LIGHTNING WAVEFORM CHARACTERISTICS IN SEVERAL STANDARD

Standard	Waveform $t_f/t_r(\mu s)$
Japan	1/40
VDE	1/50
United State	1.5/50
IEC	1.2/50
CIGRE	3.3/77.3

B. Protection Zone Against Lightning

The protection zone against lightning in tower transmission line could be obtained by calculating the protection zone between the vertical line ground wire and conductor. The protection zone or shielding angle is aimed to protect the conductor against lightning stroke. Hence, the lightning tends to stroke the ground wire instead of the conductor phase.

To maintain the failure rate, shielding failure should be carried out by considering the height the conductor above the ground and the protection zone of transmission line. In several cases when lightning stroke the conductor phase, the flashover could be occurred and resulting the casualties if the withstand voltage of the insulation passed. The protection zone could be calculated as [3], hence in [6] that the protection zone degree generally is 20 – 45 degrees. This also said that ground wire presence could decrease the induced voltage by 50%, two ground wires reduce by 66%, three ground wires reduce by 75%, and so on.

$$\theta = \tan^{-1} \frac{x}{y} \quad (1)$$

$$r = \frac{h_1}{y} \quad (2)$$

C. Tower Modelling

The surge impedance is a key parameter to understanding the insulation coordination against the lightning strike and other transient event. In this study, the surge impedance represents by tower modelling.

The tower modelling is divided in segments between cross-arms. Each segment is represented by the gap between each conductor structure. In [4] the tower modelling could be divided into three categories, single vertical lossless models, multiconductor models, and multi-story model.

Multi-story model is used in this study, where each segment of the tower consists of surge impedance series with impedance circuit as shown in Fig.4. Each parameter of the multi-story parameters is derived by equation (3) to (8) [5].

$$R = \frac{(r_1 I_1 + r_2 H + r_3 I_2)}{H} \quad (3)$$

$$Z_{Ti} = 60 \ln \left[\cot \left(0,5 \tan^{-1} \frac{R}{H} \right) \right] \quad (4)$$

$$R = \frac{(-2Z_{Ti} \ln \sqrt{y})}{h_1 + h_2 + h_3} \times h_i \quad (5)$$

$$R_4 = -2Z_{T4} \times \ln \sqrt{y} \quad (6)$$

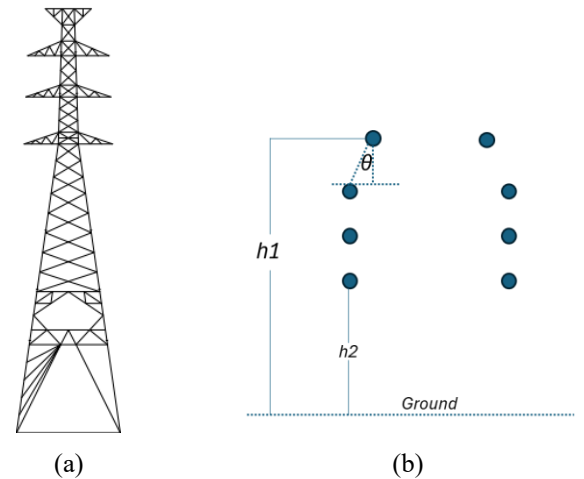


Fig. 4 (a) Tower configuration in PT. Vale Indonesia, (b) The simplify tower model

$$L_i = R_i \times \frac{2H}{v} \quad (7)$$

Where $i = 1 - 4$,
And,

$$H = h_1 + h_2 + h_3 + h_4 \quad (8)$$

Where,

- r_1 : length cross-arm of the top-tower radius (m)
- r_2 : length cross-arm of the mid-tower radius (m)
- r_3 : length cross-arm of the low-tower radius (m)
- l_1 : Radius from low to mid-tower (m)
- l_2 : Radius from mid to top-tower (m)

The proposed model was explained by Fig. 5, each segment was calculated derived from equation (3) to (8). The calculations were explained by Table 3.

TABLE 2. CONDUCTOR PARAMETER

Parameter	Value
Number of Conductor per Phase	1
Type	ACSR - Tern
Stranding (AL/STL)	45/7
Diameter	27 mm
Total Cross Sectional Area	572.26 mm ²
Weight (inc, Grease & Spacer)	1337 kg/km
Ultimate Tensile Strength	9939.17 kgF

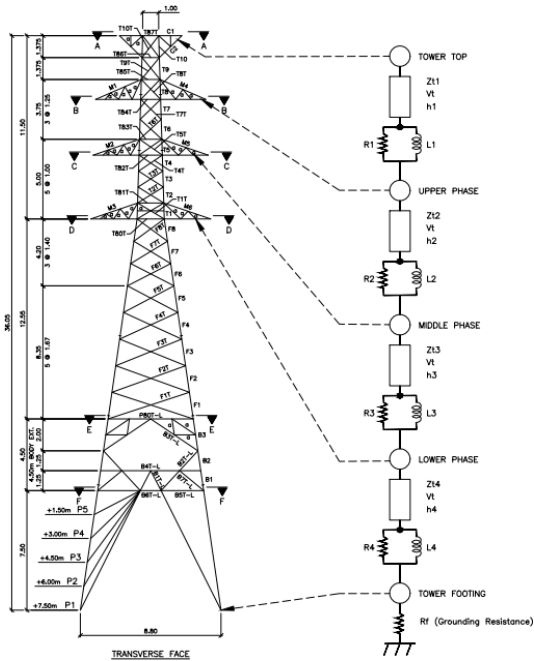


Fig. 5 Multi-story tower model for PT. Vale Indonesia Transmission Line

TABLE 3. MULTI-STORY TOWER CALCULATION

Segment		Model Tower		
		RD	RH	RL
Z_arm1	h_tower (m)	36.05	36	36
	r_arm1 (m)	1.375	1.25	1.25
	h1(m)	2.75	1.25	1.25
	Z_arm1(ohm)	320.7537	326.389	326.389
	R_arm1 (ohm)	20.90918	12.48569	12.48569
	L_arm1(uH)	5.025173	2.996564	2.996564
Z_arm2	h_tower(m)	36.05	36	36
	r_arm2(m)	1.25	1.25	1.25
	h2(m)	3.75	3.75	3.75
	Z_arm2(ohm)	326.4723	326.389	326.389
	R_arm2(ohm)	28.51252	37.45706	37.45706
	L_arm2(uH)	6.852508	8.989693	8.989693
Z_arm3	h_tower(m)	36.05	36	36
	r_arm3(m)	1	1.25	1.25
	h3(m)	5	3.75	3.75
	Z_arm3(ohm)	339.8609	326.389	326.389
	R_arm3(ohm)	38.01669	37.45706	37.45706
	L_arm4(uH)	9.136677	8.989693	8.989693
Z_arm4	h_tower(m)	36.05	36	36
	r_arm4(m)	1	1.25	1.25
	h4(m)	24.55	27.25	27.25
	Z_arm4(ohm)	339.8609	326.389	326.389
	R_arm4(ohm)	87.43838	87.3998	87.3998
	L_arm4(uH)	21.01436	20.97595	20.97595
Z_tower	h_tower(m)	36.05	36	36
	l_arm(m)	3.75	3.75	3.75
	Z_tower(ohm)	195.9241	195.8376	195.8376
	R_foot(ohm)	10	10	10
Vpeak	Vrms(kV)	150	150	150
	Vpeak(kV)	122.4745	122.4745	122.4745

TABLE 4. INSULATOR PARAMETER

Parameter	Value
Type	Pin
Nominal Voltage (kV)	20
Impulse Withstand Voltage (kV)	115
Wet power frequency Withstand (kV)	45
Power Frequency Puncture Voltage (kV)	125
Nominal Creepage (mm)	405
Total Insulator in One String	9
CFO (kV)	1125

III. RESULTS AND DISCUSSION

For this study, the transmission line that use is one of transmission lines in PT. Vale Indonesia Larona Substation – Smelting Substation. The span parameter uses actual value, surge impedance uses multi-story approaches, and ground resistance use actual data. The model that used in this study is simplified as Fig. 6.

A. The effect of lightning strike on ground wire

In this simulation, the magnitude of lightning current and the waveform of the lightning are shown in Table 4. The tower model is use as explained in previous chapter. The footing resistance of the system use actual transmission line data or maintenance data.

As explained in Fig. 7 and Fig. 8, during stroke in case A.1, the magnitude of current lightning in 1.2/50us reside for 2us. Nevertheless, in case A.2 is 1 us. The peak magnitude of both cases is 1.17 MV in upper arm, 0.78MV in middle arm, and 0.4 MV in lower arm. It shows that, the closer lightning stroke took place, the voltage rise is higher. This value affects by total surge impedance. Then for case B.1 and B.2 explained by Fig. 9 and Fig. 10, it has similar characteristics with case

A.1 and A.2, the difference between case A and B are the voltage magnitude. The voltage magnitude in upper, middle, and lower arm are 4.8, 3.2, 1.4 MV respectively. It also implies with case C.1 and C.2 explained by Fig. 11 and Fig. 12, the voltage magnitude in upper, middle, and lower arm are 11.9, 7.8, and 4.01 respectively. The result of each case shown in has similar characteristics, the difference between those cases is the magnitude of voltage in each section. The shorter front wave indicates a steeper rise in voltage over a shorter period and affect to system components response. Furthermore, the shorter front-wave implies the energy dissipation takes longer and lead to extending duration of the surge.

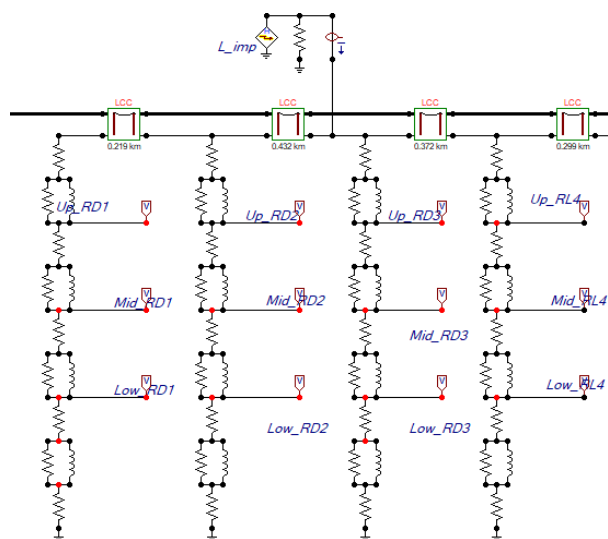


Fig. 6 Model multi-story circuit Larona Substation – Thermal Substation

TABLE 5. LIGHTNING MAGNITUDE AND WAVEFORM [5]

Case	Lightning Current Magnitude (kA)	Waveform $t_f/t_r(\mu s)$
A.1	10	1.2/50
A.2		2.59/50
B.1	40	1.2/50
B.2		2.59/50
C.1	100	1.2/50
C.2		2.59/50

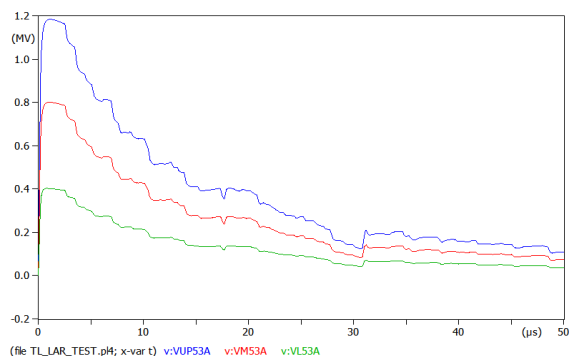


Fig. 7 The lightning response magnitude of case A.1

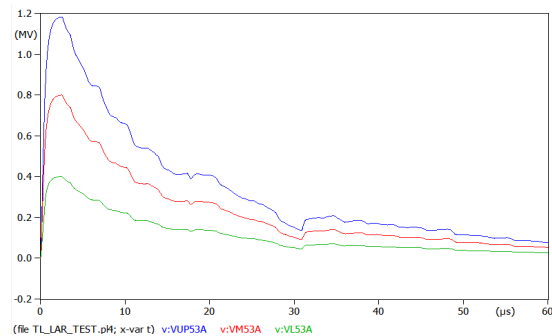


Fig. 8 The lightning response magnitude of case A.2

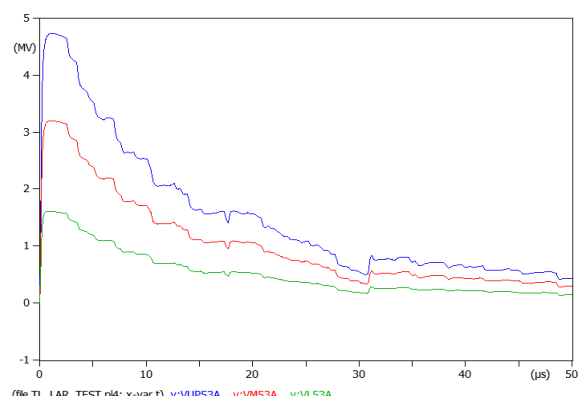


Fig. 9 The lightning response magnitude of case B.1

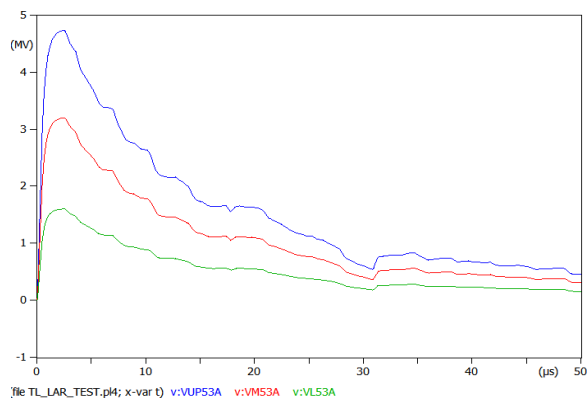


Fig. 10 The lightning response magnitude of case B.2

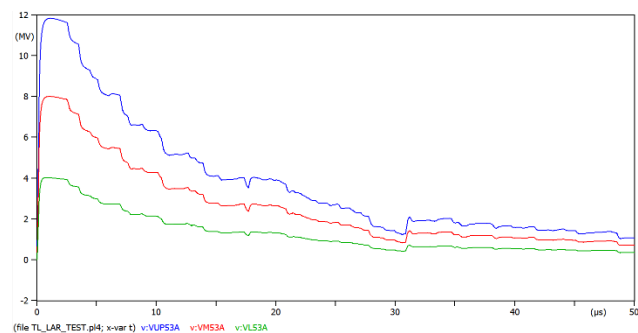


Fig. 11 The lightning response magnitude of case C.

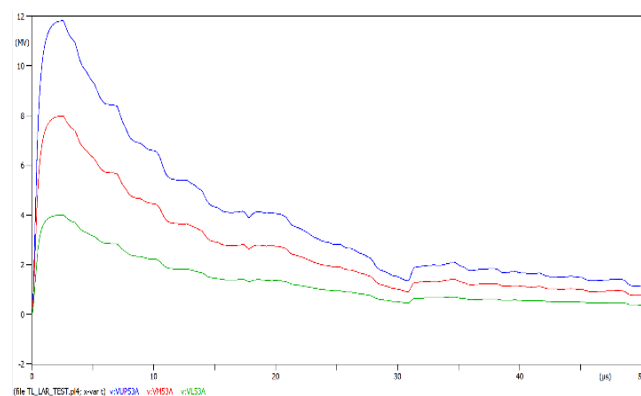


Fig. 12 The lightning response magnitude of case C.2

TABLE 6. THE VOLTAGE RESPONSE DURING LIGHTNING STRIKE

Case	Voltage Magnitude (MV)		
	Upper Arm	Mid Arm	Lower Arm
Case A.1	1.18	0.798	0.399
Case A.2	1.18	0.798	0.399
Case B.1	4.73	3.2	1.6
Case B.2	4.73	3.19	1.6
Case C.1	11.84	8	4
Case C.2	11.8	7.98	3.99

B. The total insulator breakdown due to direct lightning strike

In [5], explained that 50% of amplitude probability of lightning is 40kA, for that reason the case B.1 is chosen. In Indonesia, the common lightning waveform to perform over-voltage study against lightning use IEC standard. The lightning current is applied on tower 53A due to the highest-level topology near to Larona Substation.

In this study case, each arm of the tower using 9 insulators for each string adhere to actual condition. The basic insulation level (BIL) for each insulator is 125kV, total CFO for 9 insulators is 1125kV.

According to simulation result as shown in Table 6, the highest voltage was measured in tower 53A due to the contact point of lightning. The voltage in upper arm, middle arm, and lower arm are 3.9MV, 2.6MV, and 1.3MV, respectively. The voltage decreasing in another tower and has lowest point when away from contact point. These circumstances affect due to total surge impedance is changed. Furthermore, total insulators broken in this system are 25 possible locations. This number could be decreased by increasing the number of insulators in each string. The comparison result is shown in

TABLE 7, by increasing the number of insulators means that the BIL and CFO of the insulator increased. The simulations considered by increasing all the insulators from tower 44A to tower 57. The CFO 1500kV and 1750kV are stands for 12 insulators and 14 insulators, respectively. In 12 insulators configuration, the total possible location of insulators failure is 17. For 14 insulator configurations, the total possible location of insulators failure is 15.

C. The effect of footing resistance against lightning strike

The number of ground resistance also influences the magnitude of voltage in transmission line. The necessity of decrease the number of ground resistance is reduce potential rise, faster current dissipation, and improve system performance. According to equation (9), it was explained that the ground resistance influences the magnitude of voltage.

$$V_t = R_g I_t \times L \frac{di}{dt} \quad (9)$$

The simulation obtains that ground resistance value affected voltage rise in transmission line as explained in Fig. 13. It was expected that when FR is 3 Ohm, the voltage measured in each arm took a lowest point. When FR in range 3 – 5 Ohm, the voltage measured in tower

does not increase significantly. Nevertheless, when FR reach 10 – 20 Ohm, the voltage starts to increase. When FR reach 50 – 100 Ohm, the voltage measured increased significantly. It proved that the voltage increased significantly when FR high.

TABLE 7. VOLTAGE IN EACH ARM IN TOWER TRANSMISSION LINE

Tower	Tower Type	Voltage (kV)		
		Phase A	Phase B	Phase C
44A	RD	762.6	515.87	259.04
45A	RDH	836.02	565.57	284.03
46A	RH	901.82	602.15	302.47
47A	RDH	1002.3	669.3	336.27
48A	RDH	1205.2	815.43	409.63
49A	RH	1431	955.61	480.2
50A	RDH	1747.3	1182.4	594.22
51A	RH	2103.5	1404.3	705.02
51B	RH	2626.7	1753.6	880.56
52A	RDH	3301.7	2233.8	1122
53A	RDH	3927.4	2658.5	1337
53B	RH	3265.2	2180.36	1095.4
54A	RDH	2657.3	1797.4	902.4
54	RH	2233.2	1491.1	748.95
55	RL	2255.7	1506.1	756.62
56	RD	2092.2	1415.4	710.8
57	RD	2167.9	1466.8	736.93

TABLE 8. TOTAL INSULATOR BREAKDOWN LOCATIONS

Jumlah Isolator Breakdown			
CFO	1125kV	1500kV	1750kV
upper	13	11	10
middle	11	6	5
lower	1	0	0
Total	25	17	15

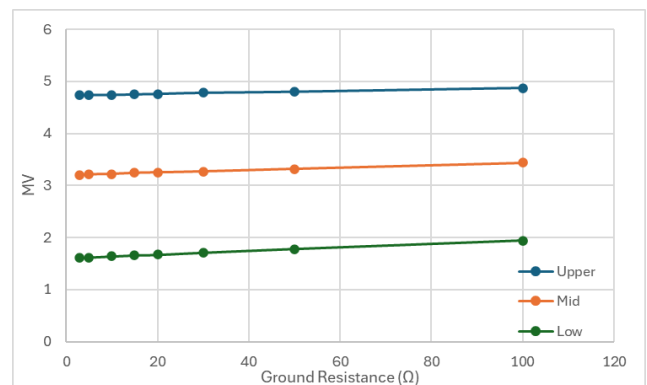


Fig. 13 Voltage on transmission line against ground resistance

IV. CONCLUSION

The simulation results presented that the over-voltages study for transmission lines is important to performed to obtain plan and designing of transmission line, the effect of GSW type, the insulator number, and the standard of grounding resistance. According to simulation results, it was shown that the increment of current lightning surge around transmission line area will be affected to the number of insulators that used on transmission line. The period of front-wave of lightning strike also affected to

voltage risen in transmission line. Furthermore, to maintain the performance of transmission line, the standard of ground resistance shall be defined, and the value of ground resistance should be maintained since the inductance of surge impedance unable to maintain. In simulation result was explain that the increment of ground resistance significantly affected to magnitude of voltage during lightning strike.

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