Numerical Modeling and Simulation in Electromagnetic Transient Program for Estimating Line Backflashover Performance

Mohd Z. A. Ab Kadir, Zawati Mohd Nawi and Junainah Sardi

Abstract— **This paper presents a numerical modeling and simulation of 132 kV transmission line in electromagnetic transient program and later predicts the critical backflashover current, probability of the transformer damage and backflashover rate (BFR) when the lightning strikes close to the substation. The electromagnetic transient program, later referred as PSCAD/EMTDC is used to model and simulate the high voltage transmission line. Various parts of transmission line such as overhead transmission line, tower, footing resistance and insulators are modeled to study the effect of lightning overvoltage, at very high frequency, on the BFR when these parameters are varied. This technique is useful in helping the utility for conducting an insulation coordination studies as the outcome can be used in technical evaluation and financial planning of the transmission systems.**

Index Terms— **Electromagnetic transient, line backflashover, numerical modeling, PSCAD/EMTDC**

I. INTRODUCTION

Lightning can cause a major impact to the transmission line. When lightning strikes a transmission line, an amount of high current will be injected to the line. This current will flow to the earth via the tower steelwork and causing a voltage difference between the tower cross-arms and phase conductors (PC) [1]. If the rise in potential at a transmission tower is large enough, a flashover will occur from the tower to phase conductor. Lightning striking transmission line is very important as it causes significant overhead line flashovers. The use of shield wires for lightning protection on overhead lines prevents most phase strikes but still results in the possibility of backflashovers. This paper presents a backflashover analysis on 132 kV overhead transmission line between 132 kV Kuala Krai substation and 132 kV Gua Musang substation through rural area of Kelantan. For the duration of January 2004 to July 2007, Lightning Detection System Lab (LDS), TNB Research indicated that the average ground strokes densities of the area on which the line route range from 6 to 20 strokes/km^2/year whilst the mean multiplicity of lightning strokes observed is 3 [2]. Based on the theoretical foundations of the backflash mechanism, it is concluded that with properly shielded lines, high voltage (HV) and extra high voltage (EHV) lines can be economically designed for a trip-out rate averaging approximately 0.25 per 100 kilometres-years for an area with a thunderstorm day level of 40 per year [1,3].

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II. TRAVELING WAVE BEHAVIOR OF OVERHEAD LINES

Any disturbance on a transmission line such as a lightning stroke or any interruption of the steady state condition, results in the initiation of travelling waves. These disturbances propagate towards the end of the lines with a specific velocity, where they may be reflected and modified. It then attenuates and is distorted by corona and other losses until it does not appear anymore.

In practical terms, it can be stated that a lightning stroke to a conductor or the closing of a breaker produces travelling waves of voltage e and current i that are related by a surge impedance Z equal to e/i that travels along a conductor at approximately the speed of light c as portrayed by Fig. 1.
The surge impedance Z is purely resistive; therefore, e and i have the same shape. The surge impedance and velocity of propagation can be obtained from the inductance and capacitance per unit length, which are $Z=\sqrt{\frac{L}{C}}$ and $v=\frac{1}{\sqrt{LC}}$, respectively. By solving these two equations, the following useful relationships can be obtained, i.e. $L=\frac{Z}{v}$ and $C=\frac{1}{Zv}$, where L and C are the inductance and capacitance per unit length respectively.

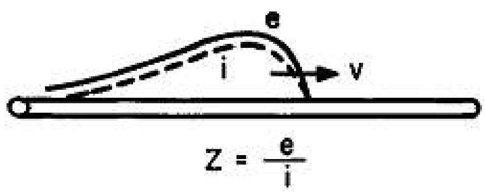

Figure 1. Relationship between e and I.

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For a single conductor having a radius r and height h above ground and relative dielectric constant of the surrounding medium ε_r (=1 for air), the self inductance and capacitance are $L = 2\times10^{-7}\ \ln\frac{2h}{r},\ H/m$ and $C = \frac{\varepsilon_r 10^{-9}}{18\ln\frac{2h}{r}},\ F/m$

In case of a bundle conductor, *r* in the equation above is replaced by the equivalent radius of the line conductor, i.e. $r_{eq} = \left[n r_{sc} A^{n-1} \right]^{1/n}$ where *n* is the number of subconductor per phase, r_{sc} is the radius of a conductor and A is a bundle radius. By substituting L and C in the previous equations, the velocity of the travelling waves is obtained as $v = \frac{3\times10^8}{\sqrt{\varepsilon_r}}$, m/s

In air (ε_r =1), c =300 $m/\mu s$, which is the velocity of light in free space. For a cable, ε_r varies from 2.4 to 4.0 [3].

A travelling wave is usually characterized by four parameters [4] as shown in Fig. 2(a) and 2(b). The *crest* of the wave is its maximum amplitude. The *front* of the wave is the time from its beginning to the crest. However, for waves having a slow rate of rise (a long toe) followed by a rapid rate of rise and then leveling-off to the crest, it is customary to ignore the slower rate of rise and to consider the effective front, which is between 10 and 90% points. This is shown by Fig. 2(b). The portion that is beyond the crest is called the *tail*, which is the point when the crest is decreased to half value. The last part is the *polarity* of the crest.

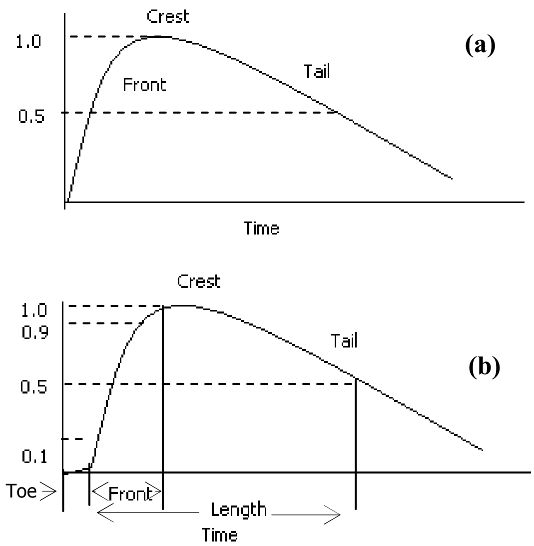

Figure 2. Specification of a travelling wave

An accurate model of a transmission line must take into account the uniformly distributed r, l, c and g of the line. Fig. 3 shows a small element in a long transmission line.

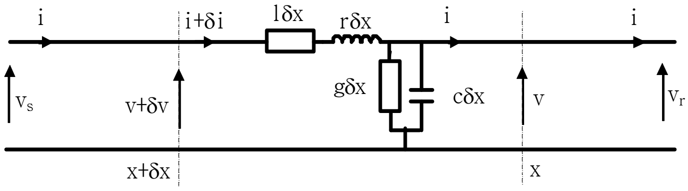

Figure 3. Transmission line element model for use in travelling wave equations.

In the picture:
r = series resistance per unit length
l = series inductance per unit length
c = series capacitance per unit length
g = series conductance per unit length

The voltage and current equations of transmission line can be expressed as $V = \frac{V_r + I_r Z_c}{2} e^{\gamma x} + \frac{V_r - I_r Z_c}{2} e^{-\gamma x}$ and $I = \frac{V_r + I_r Z_c}{2Z_c} e^{\gamma x} + \frac{V_r - I_r Z_c}{2Z_c} e^{-\gamma x}$. The terms γ and Z_c are the *propagation constant* and *characteristic impedance* of the lines and are written as $\gamma = \sqrt{zy}$ (m^{-1}) and $Z_c = \sqrt{\frac{z}{y}}$ (Ω), respectively where $z = r + sl$ and $y = g + sc$ with s is the Laplace transform of the equation. In real or lossy lines, both the waveshape and energy change due to the resistance of the line. However for a lossless line, where is no resistance on the line, the waveshape only will change. This is because of the inductance and shunt capacitance acting as a low pass filter but the energy remaining the same. In insulation coordination studies, lossless overhead lines are normally used in calculations. This can be a valid approximation since at high frequency, ωl and ωc are larger than r and g. As the travelling wave (high frequency signal) propagates down the line its magnitude decreases. Reflections of travelling waves also occur at surge impedance discontinuities and these can also be explained from the equations below. Each waveform is formed from a forward and reflected voltage and current component which are $V_{terminal} = V_{incident} + V_{reflected}$ and $I_{terminal} = I_{incident} + I_{reflected}$, where, $V_{terminal}$ and $I_{terminal}$ are the voltage and current respectively at the end of a line.

From basic circuit theory, the current at the receiving end is equal to $I_{terminal} = \frac{V_{incident}}{Z_c} - \frac{V_{reflected}}{Z_c}$. Now, the reflected and terminal voltages and currents can be related to the incident voltages and currents can be expressed by

$$V_{terminal} = V_{incident} \times \frac{2Z_{terminal}}{Z_C + Z_{terminal}} = a_t V_{incident},$$

$$V_{reflected} = \frac{Z_{terminal} - Z_C}{Z_{terminal} + Z_C} V_{incident} = a_r V_{incident},$$

$$I_{terminal} = I_{incident} \times \frac{2Z_C}{Z_C + Z_{terminal}} = b_t I_{incident},$$

$$I_{reflected} = -\frac{Z_{terminal} - Z_C}{Z_{terminal} + Z_C} I_{incident} = b_r I_{incident}$$

From the above equations, depending on the characteristic and termination impedances, Z_t of the line or cable, the respective reflection or transmission coefficients can be evaluated. Table 1 summarises the reflection and transmission coefficients for the most common cases.

Table 1. Summary of transmission and reflection coefficients for the most common cases.

Line Terminated With:	a_t=voltage transmission coefficient	a_r=voltage reflection coefficient	b_t=current transmissio n coefficient	b_r=current reflection coefficient
Line Surge Impedance	1	0	1	0
Short Circuit	0	-1	2	1
Open Circuit	2	1	0	-1

From Table 1, there is no voltage or current reflected in the case of line terminated with the line surge impedance. In the short circuit case, there is no voltage at the short circuit end. A negative reflection will travel back towards the injection point and neutralize the reflected wave. In contrast, the terminal current will be doubled and produced a positive reflected wave. For an open circuit, no current flowing into the terminal and all the current is reflected. The terminal voltage becomes double.

III. Numerical modeling technique in EM Transient program

A. Modeling of Transmission Line

Overhead transmission line is modeled using Frequency Dependent (Phase) Model which uses curve fitting to duplicate the frequency response of a line or cable. It is the most advanced time domain model available as it represents full frequency dependence of all line parameters (including the effect of a frequency dependent transform). The Frequency Dependent (Phase) model is a distributed RLC traveling wave model, which incorporates the frequency dependence of all parameters. This model represents the frequency dependence of internal transformation matrices. Hence, it is useful for studies wherever the transients or harmonic behaviors of a line or cable is important [5]. Each span is represented by a multiphase untransposed line model and the phase conductor and shield wire are explicitly modeled between towers [6].

B. Modeling of Lightning Stroke

Lightning stroke is represented by a current source of negative polarity. The peak current is statistically related to the steepness or time to crest of the current waveform. The steepness increases as the peak current increases, however, the front time increases with peak current. Equations $P(I) = 1/\left(1+(I/31)^{2.6}\right)$ and $t_f = I/(24((1/P(I))-1)^{0.25})$ are used to calculate statistical data for amplitude and steepness of lightning current [7], where parameters I = lightning current in kA, P(I) = probability the stroke current equals or exceeds the critical backflashover current and t_f = front time in second.

C. Modeling of Tower

Tower is modeled using several segments of single conductor distributed parameter model or Bergeron model [6]. The surge impedance of the transmission line tower and the tower travel time of wave propagation down the tower are required. Surge impedance for each tower in the Kuala Krai – Gua Musang line is provided by TNB and its value range 100 – 200 ohm. For each case of tower structures, the travel time from tower top to ground can be estimated as $\tau = \frac{h}{c}$, where h = height of the tower in meter and c = speed of light, 3 x 10^8 $ms^{-1.}$ However, IEEE practice is to modify the propagation time along the tower to account for the extra path length of cross-arms, leading effectively to a speed of 0.85 of the speed of light, c. Fig. 4 shows the tower configuration and its dimensions for the 132 kV Kuala Krai-Gua Musang line in Malaysia [2].

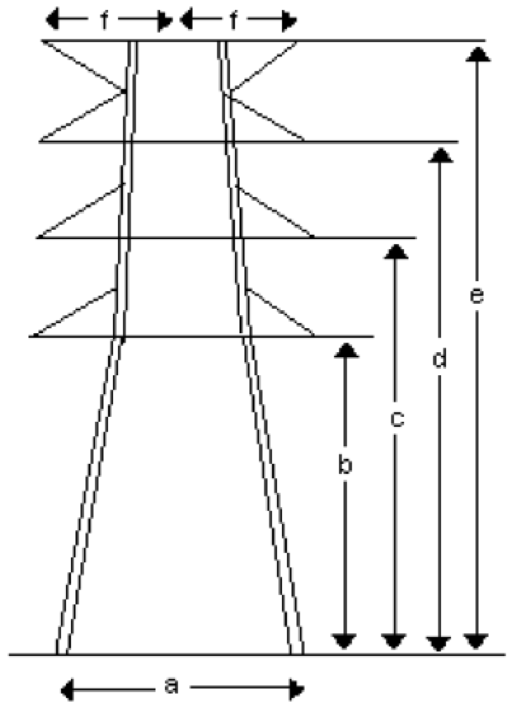

Figure 4: Configuration of a 132kV transmission tower with a = 5.7m, b = 18.9m, c = 22.56m, d = 26.22m, e = 30.54m and f = 4.42m [2].

D. Modeling of Footing Resistance

Tower footing is determined using current dependence of tower footing resistance of $Rt = \frac{Ro}{\sqrt{1+\frac{I}{Ig}}}$ and $Ig = \frac{1}{2\pi} \times \frac{Eo\rho}{Ro^2}$ [8], where parameters R_t = tower footing resistance, R_o= tower footing resistance at low current and low frequency, I = lightning current, kA, I_g = limiting current, kA, ρ = soil resistivity, Ωm, Eo = soil ionization gradient, ($\approx$300kV/m)

E. Modeling of Insulator

The insulator string model can be based on the leader progression model. Streamers propagate along the insulator string when the applied voltage exceeds the corona inception voltage; if the voltage remains high enough, these streamers will become a leader channel. A flashover occurs when the leader crosses the gap between the cross-arm and the conductor. The total time to flashover can be expressed as $t_t = t_c + t_s + t_l$, where t_c is the corona inception time, t_s is the streamer propagation time, t_l is the leader propagation time. Usually t_c is neglected, while t_s is calculated as $t_s = \frac{E_{50}}{1.25E - 0.95E_{50}}$. The leader propagation time t_l, can be obtained using $\frac{dl}{dt} = kv(t)\left[\frac{v(t)}{g-L} - E\right]$, where v(t) is the voltage across the gap, *g* is the gap length, *L* is the leader length, *E* is the critical leader inception gradient and *k* is a leader coefficient and is given in reference [9].

IV. Description of Simulation Model and Cases Studied

Fig. 5 shows the system modeled for analyzing the backflashover. The last four towers are chosen to demonstrate the effect of the lightning surge overvoltage, injected at tower 295 (the last tower) close to substation, on the voltage level measured at the substation entrance. The grounding resistance for the substation is assumed to be 10 ohm. Total line length used in the modeling is approximately 1681 meters, which the line spans can be seen in Fig. 4. One end of the line is terminated with matching surge impedance while the other end is represented by a 132 kV transformer at the substation (equivalent capacitance value used to represent the transformer, TX is obtained from **[**9**]**, which is calculated based on the IEEE WG 3.4.11 **[**10**].** Table 2 shows the line details while Table 3 depicts the key parameters used in the modeling.

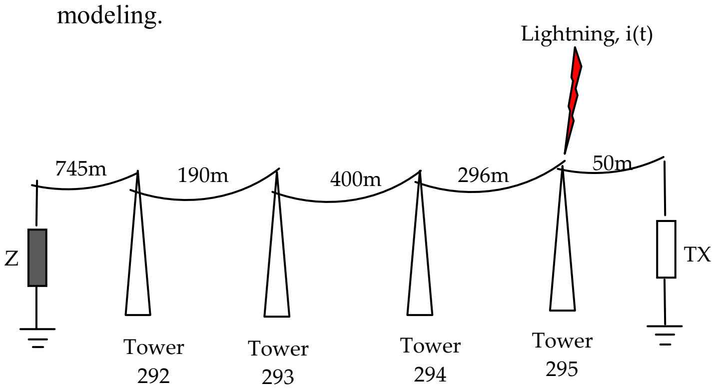

Figure 5: System modeled for backflashover analysis

Table 2: 132 kV Kuala Krai-Gua Musang line details

Item	Details
Starting Substation	Kuala Krai
Ending Substation	Gua Musang
No of towers	295
Total line length (km)	112.81
Conductor Data	1 x 300mm2 Batang
Insulator Data	14 disc x 146mm
Line sag (max)	8.89m
Average Ground Flash Density	4 flashes/km2/year
No of Tripping (Jan2004 – July2007)	13
Backflashover Rate	4.19 flashes/100km/year

Table 3: Key parameters used in modeling for 132 kV system.

Model	Sub-Component	Details/Reference
Lightning Strike		Double exponential current source with a varying front time according to the peak current.
Overhead Line	Shield wire	1 shield wire, 12.95mm diameter (Skunk) and surge impedance of 537 Ω. The shield wire is terminated at the substation with a 10 Ω resistance.
	Phase Conductor	Single phase conductor, 24.16mm diameter (Batang) and surge impedance of 300 Ω. The transformer is represented as a capacitor with value of 1485.13pF.
Tower	Main Structure	Surge impedance (range from 128 Ω to 143 Ω). Travelling wave velocity of speed of light modeled with a Bergeron model.
	Tower Footing	Ground resistance (range from 47.8 Ω to 557.5 Ω) and soil resistivity of 3000 Ω m.
	Coordination Gap	Modeled with a leader progression model (LPM) with the gap distance of 2.04 m

Table 4 shows the actual parameters of the tower surge impedance, footing resistance and soil resistivity. Data for the footing resistances and soil resistivities are provided by TNB whilst values of the tower surge impedance are calculated based on the IEEE WG [6] guideline.

Table 4: Actual parameters of tower surge impedance (calculated), footing resistance (provided) and (soil resistivity (provided) designed for each chosen tower

Tower No	Tower surge impedance (Ω)	Footing resistance (Ω)	Soil resistivity (Ω m)
292	139.979	557.549	3000
293	142.995	47.83	3000
294	128.144	47.83	3000
295	130.338	557.549	3000

In terms of the studies, Table 5 shows six different cases that are considered to demonstrate the effect of variations in parameters on the BFR. As reported by Cotton and Ab Kadir [11], location between point-of-attachment (POA) of the lightning and the tower top will also give variations in results. Depending on the location of the leader progression model (LPM), the farther the POA from the LPM, the higher the current needed to breakdown the insulator coordination gap on that particular tower. Taking this matter into account, the POA close to the substation is chosen to demonstrate the seriousness of the impact having the transmission line with a poor performance and in high ground flash density area. Case 1 is simulated according to the actual data as per Table 4 with only one shield wire. Cases 2 and 3 are simulated with the changes of footing resistances of 47.83 and 557.549 Ω respectively. These two values are expected to give a variation in the result. Case 4 is based on the actual data of footing resistance, except the soil resistivities for all towers are changed to 100 Ω m. Case 5 is with the changes of both footing resistances and soil resistivities for all towers to 10 Ω and 100 Ω m respectively. This is the ideal situation where both parameters are lower in values and hence the reduction in BFR is expected from the result obtained. Lastly, Case 6 with the same parameters as Case 1, except it has two shield wires, is to demonstrate the effectiveness on having more shield wires for protection especially in the area with high ground flash density.

Table 5: Comparison of cases studied

Case	**Footing resistance for all towers(Ω)**	**Soil resistivity, ρ (Ω m)**	**No of shield wire**
Case 1	Actual values	Actual values	1
Case 2	All tower 47.83	Actual values	1
Case 3	All tower 557.549	Actual values	1
Case 4	Actual values	All tower 100	1
Case 5	All tower 10	All tower 100	1
Case 6	Actual values	Actual values	2

The outcomes or results from the simulation will be the probability of transformer damage based on the value of Basic Insulation Level (BIL) and the BFR for all cases. Currently, the BIL of transformer used by TNB is 550 kV.

V. Result and Discussion

Critical backflashover current, I_C

In terms of the critical current, Cases 1 and 3 give the same values of 51 kA compared to the Case 5 which demonstrates the effective protection capability and high performance. With high footing resistance and high soil resistivity, lower current is expected to break the insulator coordination gap. As a result, soil will ionize quicker and the negative reflection travels back to the tower top without helping much in reducing the overvoltage. Whilst, for Case 5, a combination of low soil resistivity and low footing resistance will reduce the surge overvoltage at the tower top and therefore high current is needed for the gap to breakdown. The same trend demonstrated by Case 3. Although its footing resistances are set to the higher values compared to Case 5, it can be seen that a higher critical current is needed for the gap to breakdown. This is due to the proper grounding at the substation (10 Ω), which provides better negative reflection to decrease the voltage level at the POA. However the distance between the last tower and the substation, as well as the height the tower itself, also play an important role in determining the significance of the impact of incoming surge at the substation. Therefore, from the protection point of view, the surge arrester may need to be employed at the substation entrance in the addition of the proper earthing arrangement as suggested in the standard.

Probability of transformer damage

By comparing the maximum voltage measured at the substation entrance, V_{max} and the BIL of the transformer, which is 550 kV, a set of result can be generated showing the probability of the transformer damage for each case. This is shown in Table 6. The higher the voltage level, the higher the probability of the transformer damage. As the probabilities varied in between 18% to 89%, significant differences observed in the results of Cases 3 and 1 which appear to give higher probabilities of the damage i.e. 89% and 79% respectively. The lowest percentage of probability obtained by Case 5 that is 18%, although this is still not the expected result from the utility point of view. Therefore, when it comes to the insulation coordination study, it is indeed a very interesting point to look into the selection of BIL. As highlighted in the standard such as the IEC standard, there are two options of BIL values for 132 kV i.e. 550 and 650 kV. The selection of 650 kV as the BIL will definitely provide greater protection compared to the case of 550 kV. However, one should carefully note that with the option of 650 kV BIL, this will increase in the cost per unit item and the physical size of the transformer itself. In contrast, with the 550 kV BIL, the user can choose for a less cost and less protection margin. Thus, it can clearly be seen the importance of knowing the risk and selection of the right BIL for the equipment.

Backflashover rate (BFR)

The resultant BFRs, which are dependent on the critical backflashover current I_C, show that the higher the critical current, the lower the BFR value is. This BFR depicts the performance of the transmission line as the lower BFR indicates that the line is well-shielded and can sustain from the surge overvoltage and vice versa. As mentioned earlier, the combination of low soil resistivity and low footing resistance will reduce the surge overvoltage at the tower top. Therefore high current is needed for the gap to breakdown and thus will result in lower BFR, as demonstrated by Cases 2 and 5. In addition, the use of two shield wires will lower BFR value compared to the case of having just a single shield wire. Again, Table 6 shows the significant differences in terms of the lightning current and the maximum voltage measured at the substation entrance. Line with two shield wires has a higher withstand capability and of course it is well protected compared to the line with only one shield wire. This may not be an issue if the BFR is clearly determined during the early construction of the line where all line parameters such as height of the towers, the size and length of the insulator strings, the angle of shield wire, the need for line arrester (area with high ground flash density) and others can properly be done and justified. As the financial planning will always be the main issue, it is indeed really important to have compromising thoughts between the protection margin and the cost.

Table 6: Result for each case for lightning strikes to tower 295

Case	I_C, (kA)	V_{max}, (kV)	Probability of transformer damage, (%)	BFR
1	51	848	79	11.2
2	147	895	26	0.9
3	51	953	89	11.2
4	79	988	65	4.2
5	157	572	18	0.8
6	83	1728	62	3.7

VI. CONCLUSION

Effect of variations in line design parameters have successfully been simulated and analyzed using numerical modeling and simulation technique in electromagnetic transient program of PSCAD/EMTDC. This technique is used for investigation and assessment of the transmission line performance based on the BFR values obtained. As far as the application of electromagnetic program is concerned, this is another application of what has been proposed in [12]. Results show that high soil resistivity coupled with high footing resistance will increase the critical backflashover current and so does the BFR. Well shielded line with two shield wires is also another factor in decreasing the BFR compared to a single shield wire. Higher probability of the transformer damage is shown by Cases 1 and 3 due to the lower voltage measured at the substation entrance when compared to the BIL of 550 kV for 132 kV transformer. In addition, lower values of critical currents obtained show that the line is prone to the insulator coordination gap breakdown. Lightning performance of the line can be improved if some modifications or improvements are made to the line such as improving in footing resistance and install surge arrester at the line especially at the rogue towers. Proper counterpoise arrangement for instance can be used to obtain acceptable footing impedance. During lightning event, a given length of counterpoise with many radial sections attached to one tower will provide lower dynamic impedance that that the same total length of continuous counterpoise. However, when soil condition (e.g. rocky terrain) does not permit the installation of counterpoise, line arresters are an excellent alternative, with proper selection and arrangement. Overall, it is clear that the choice of proper modeling technique will benefit the utility in assessing the performance of the transmission line. Accurate modeling and reliable results obtained later can be used in evaluating the need for proper protection scheme to the line and thus increase the quality of electricity supplied. For economical insulation coordination in transmission and substation equipment, it is necessary to accurately predict the lightning surge overvoltages that occur in an electric power system. These overvoltages will provide the data required for any mitigation method such as employment of surge arrester. Then, the insulation level (BIL) of the substation equipment can be coordinated with probability of voltage exceeds BIL. Therefore, probability of voltage exceeds BIL computed in this research can be used as reference in selecting the right mitigation method and minimum insulation requirement to reduce the probability of transformer damage at substation. Therefore, this electromagnetic transient modeling approach clearly provided another perspective in modeling and analyzing the effect of lightning on transmission line.

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