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Analysis of a back flashover across insulator strings on a 115 kV transmission line tower by PSCAD

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Abstract

Lightning striking on a transmission tower induces high ground potential rise and high voltage at tower arms in which potential is normally at ground level, and subsequently causes overvoltage across an insulator string. If this overvoltage is higher than the withstanding voltage of the insulator string according to the v-t (voltage-time) curve, back flashover phenomena will occur and this event may cause outage. The main objective of this paper is to study the factors influencing the back flashover phenomena. The computer program PSCAD/EMTDC (Power System Computer Aided Design/Electromagnetic Transients including DC) is used to simulate lightning striking on a transmission tower 115kV. Lightning current, transmission towers, ground resistance, insulator strings and back flashover phenomena are modeled. Main simulations are lightning striking on different towers, different soil resistivity, different lightning current magnitudes and wave shapes, different locations, and different phase angles of source voltage. Simulation results show that the higher tower encounters higher induced voltage. A back flashover occurs at the top tower arm easier than at the middle and lower arms. The higher soil resistivity induces higher voltage. The larger lightning current magnitude impacts on higher induced voltage. The longer rise time of lightning current generates lower induced voltage. Lightning strikes directly on tower generate higher voltage than that of striking on overhead ground wires.

Keywords : Lightning, Back flashover, Insulator string, PSCAD/EMTDC

1. Introduction

Transmission towers are always located in a long distance between sources and loads. Overhead ground wires are used to protect transmission lines below. Insulator strings hanging down between tower arms and transmission lines are used as an insulation to isolate electrical path. Tower is grounded to provide convenient path for large current. Lightning may directly strike on either transmission tower or overhead ground wires. Lightning current flowing through transmission tower to earth causes high induced voltages (IDV) at tower arms. If this IDV is higher than the withstand voltage of the insulator strings according to the v-t (voltage-time) curve, back flashover phenomena may occur. Back flashover (BFO) is a flashover event across insulator string, from tower to line. Protection system considers flashover as a power line failure, thus protection devices are operated, transmission line is de-energized leading to outage i.e. outage in south region of Thailand in 2013 [1].

Travelling wave theory is used to analyze reflecting/refracting voltages. Waves travel back and forth on transmission tower. Every time it reaches the junction points with unequal impedance, reflection and refraction waves are generated. When waves meet each other, they will merge and then separate while they pass each other. It is too complicated to analyze these traveling waves by hand. Thus, many efficient computer programs are used to produce IDV caused by lightning.

A critical 220 kV transmission lines in Sri Lankan was studied due to several past records of lightning back flashover [2-3]. It was simulated by a computer program, PSCAD/EMTDC to study the improvement transmission lines with and without lightning arrester.

Analysis of tower footing resistance effecting BFO phenomena on 115 kV transmission lines in north of Thailand was carried out [4]. Analysis study of some parameters effecting BFO was carried out by using ATP (Alternative Transients Program) software program [5]. The effect of lightning wave shape on back flashover phenomena was simulated by EMTP (Electro Magnetic Transients Program) program [6].

This paper studies the important factors influencing BFO across insulator string using PSCAD/EMTDC. Comprehensive cases are simulated and analyzed. First, simulations without system source voltage are carried out to study IDV caused by lightning strike, and important factors influencing the IDV. Finally, the system source voltage is then added to study of the resulting overvoltages. BFO phenomena in each case is summarized.

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2. Component modeling

The objective of this paper is to study factors influencing back flashover phenomena simulated by PSCAD/EMTDC. First, each component is modeled and verified. They are then integrated in a complete simulation system shown in Figure 1. The effects of each interesting factor are studied carefully.

2.1 Lightning current

Lightning current (LC) is uni-direction and in range up to several of 10 kA [7]. Peak values can exceed 100 kA. The highest value of LC ever recorded is 200 kA. In [8],LC magnitude of low level 10 kA was used to produce a short striking distance to prevent protruding of smaller LC. The rise time (T_1) is in range 0.1–10 μs or more, whereas, the tail time (T_2) is in range 0.1–2 ms [7]. Thus, LC used in this paper is in range 30–200 kA. LC wave form is specified in front time/tail time (T_1/T_2), shown in Figure 2. LC rises from zero to peak value (T_1) very fast, then decays to half of peak values (T_2) slowly. LC model is shown in Figure 3. The peak value in kA, rise time and tail time can be conveniently adjusted. Three LC waveforms in T_1/T_2, 1.2/50 μs , 8/20 μs and 30/60 μs [2-3], are used.

2.2 Transmission tower

Loss-less, constant parameter distributed line (CPDL) model [2-4] is employed and shown in Figure 4. It comprises series surge impedance for each section. Surge impedance (Z_T) is calculated from (1). The values of r_1-r_3, x_1-x_4, andh_1-h_2 are obtained from tower configuration.

$$Z_T = 60\ln[\cot\{0.5\cdot\tan^{-1}(\frac{R}{h})\}] \tag{1}$$

$$R = \frac{r_1 h_2 + r_2 h + r_3 h_1}{h} \tag{2}$$

$$h = h_1 + h_2 \tag{3}$$

$$\tau = \frac{h}{c} \tag{4}$$

$$R_i = \frac{x_i}{h}\cdot 2Z_T \ln(\frac{1}{\alpha}),\ i = 1, 2, \ldots, 4 \tag{5}$$

$$L_i = 2\tau R_i,\ i = 1, 2, \ldots, 4 \tag{6}$$

h :total height of tower (m)

α : attenuator factor (0.89)

c :wave velocity ($3\cdot 10^8$ m/s)

R_i : resistance at section i of tower (Ω)

L_i : inductance at section i of tower (H)

Four tower types: A, B, C and D, are ones of many types used in Thailand shown in Figure 5. Type A and B are used for 115 kV system, whereas type C and D are used for 230 kV and 500 kV system, respectively. Type B is the shortest tower whereas type D is the highest one. The parameters of tower each type, are shown in Table 1. The parameters, R_i, L_i are obtained from (5) and (6).

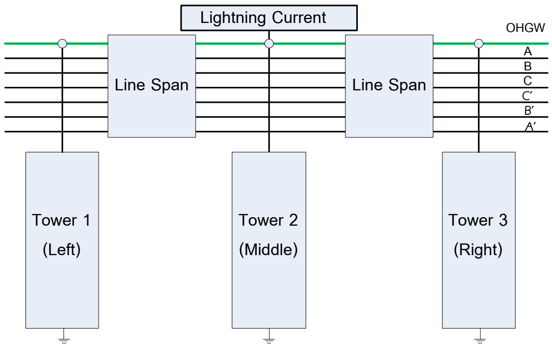

Figure 1 Complete simulation system

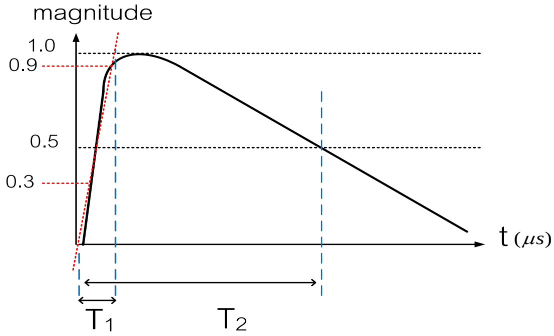

Figure 2 Lightning current waveform

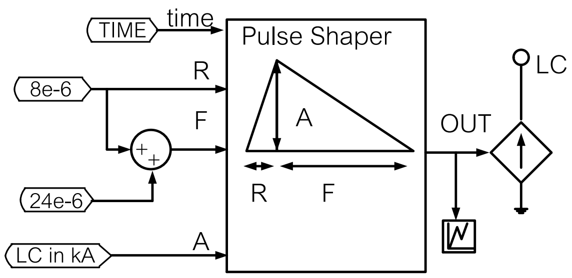

Figure 3 Lightning current model

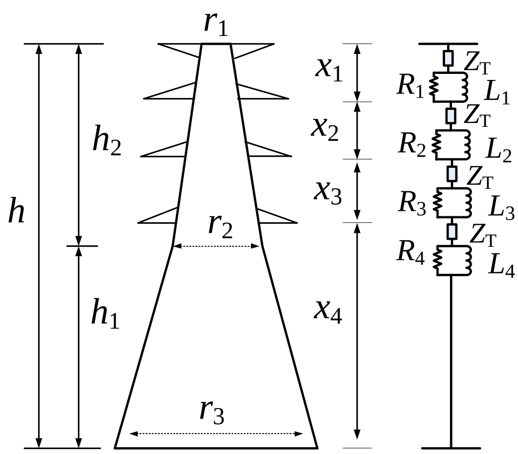

Figure 4 Transmission tower model (CPDL) for waist tower

Table 1 Tower parameters

	Tower			
	Type A	**Type B**	**Type C**	**Type D**
Z_T (Ω)	172.67	153.44	137.59	134.10
R_1 (Ω)	3.57	3.81	3.70	5.38
R_2 (Ω)	4.05	4.08	4.52	5.38
R_3 (Ω)	4.05	4.08	5.35	5.38
R_4 (Ω)	28.58	23.80	18.50	15.11
L_1 (H)	0.80	0.67	0.96	2.29
L_2 (H)	0.91	0.72	1.18	2.29
L_3 (H)	0.91	0.72	1.39	2.29
L_4 (H)	6.44	4.17	4.81	6.44
h_1, h_2 (m)	22.2, 11.6	17.5, 8.8	22.5, 16.5	30.9, 33.0
r_1, r_2,	1.08, 1.08,	1.15, 1.15,	1.25, 2.93,	4.6, 4.8,
r_3 (m)	3.6	3.8	7.8	14.18
x_1, x_2,	3.0, 3.4,	2.8, 3.0,	4.5, 5.5,	11.0, 11.0,
x_3, x_4 (m)	3.4, 24	3.0, 17.5	6.5, 22.5	11.0, 30.9

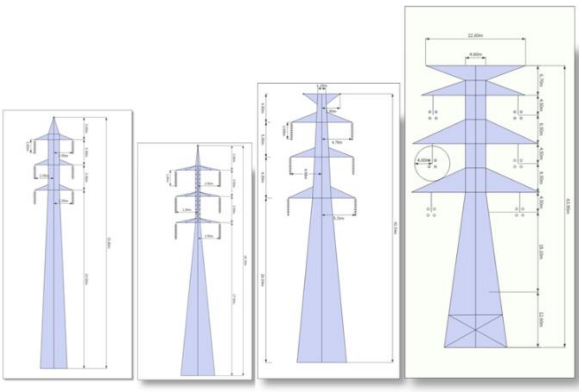

Figure 5 Different types of transmission tower

2.3 Tower footing resistance

Tower grounding system may use four ground rods, shown in Figure 6. The resistance of one ground rod (R_g) is calculated from (7). Assumed that four ground rods are buried deep at each corner. The effective ground resistance (R_o) is obtained from (8). Tower footing resistance (R_f) obtained from (9) [2-3], depending on R_o and LC magnitude (I) due to soil ionization.

$$R_g = \frac{\rho}{2\pi l}[\ln(\frac{4l}{a})-1] \tag{7}$$

$$R_o = 1.36 \cdot \frac{R_g}{4} \tag{8}$$

$$R_f = \frac{R_o}{\sqrt{1+\frac{I}{I_g}}} \tag{9}$$

where $I_g = \frac{1}{2\pi}(\frac{\rho E_o}{R_o^2})$ (10)

ρ : soil resistivity ($\Omega \cdot m$);

E_o : soil ionization gradient (300 kV/m);

I : lightning current magnitude (kA)

l : rod length in earth (m)

a : rod radius (m)

2.4 Transmission line and overhead ground wire

Transmission line and overhead ground wire (OHGW) are modeled in Figure 7-8. Frequency model is used since it is in transient periods which there may be various frequencies due to LC wave shape. For tower with two circuits and one OHGW, the total number of conductors is seven. TLine in Figure 7 is represented transmission lines and OHGW whereas line interface is used to connect with other components. Two layers are used for better understanding. The expanding detail in deeper layer of component TLine is shown in Figure 8. The position of lines and OHGW, conductor diameter and frequency model are input in this level.

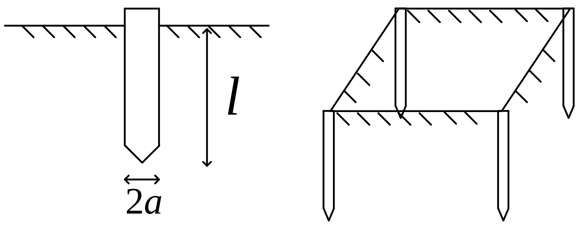

Figure 6 Transmission tower grounding system

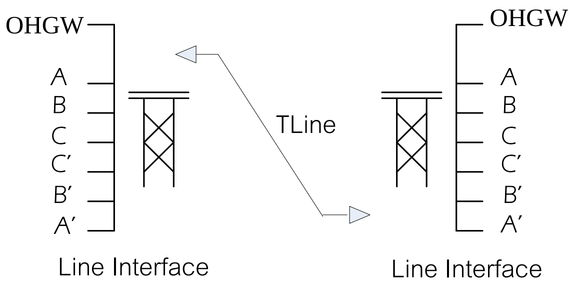

Figure 7 Transmission line model

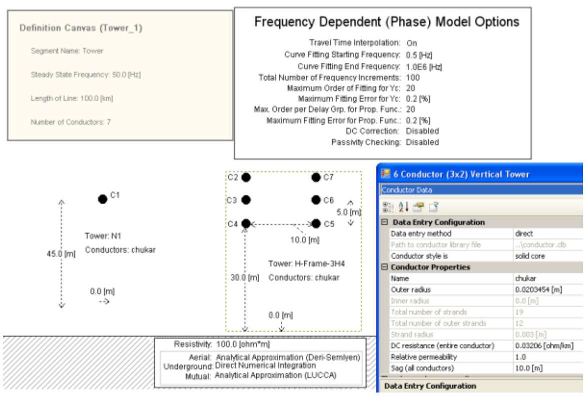

Figure 8 Conductor configurations

2.5 Insulator string

An insulator string comprises many insulators i.e. 7 insulators, type ANSI 52-3, in a 115 kV system as shown in Figure 9. Flashover voltage (V_{fo}) is calculated from (11) depending on elapsed time (t). At the very short time (t<1 μs), V_{fo} is very high and lower when time t increases as shown in Figure 10 known as v-t curve. At any time, if IDV across insulator string is higher than V_{fo}, BFO occurs as shown in Figure 11. Thus, they must be compared all the time during LC time. Insulator string is modeled with a capacitor parallel with a circuit breaker (CB) as shown in Figure 9. CB contact operation control signal is obtained from comparative logic as shown in Figure 12. Whenever IDV across insulator string is higher than V_{fo}, comparative model will generate a signal to close CB contact representing BFO event. In each simulation, IDV at every tower arm and BFO events are recorded.

$$V_{fo} = K_1 + \frac{K_2}{t^{0.75}} \tag{11}$$

where $K_1 = 400 \cdot A_g$ (12)

$$K_2 = 710 \cdot A_g \tag{13}$$

A_g : arcing horn gap length (m)

t : elapsed time after lightning strike (m)

2.6 System source voltage

Since power frequency is 50 Hz, the time period is very long compared to LC rise/tail time. Thus, at the instant time of lightning strike, system source voltage is seen as a constant value and modeled as shown in Figure 13. The phase angle between phase in a three phase balanced system, is ±120 degree different resulting in different values for each phase at any instantaneous time. Input parameters are V_{peak} (peak value of source voltage) and phase angle of phase A.

3. Numerical results

The simulations are carried on 3 cases: case A, case B and case C. They are subdivided into many subcases as shown in Table 2. Tower type A is used as a common one in each case.

IEC 60060-1 defines many exponential lightning impulses with different wave shapes, thus different rise times i.e. 1 μs, 4 μs, 8 μs and 30 μs were used to simulate service condition of an arrester in [9]. In case A1, three LC waveforms of 1.2/50 μs, 8/20 μs and 30/60 μs are used to study the impact of LC rise time. These LC wave shapes were used in [2-3]. In case A2, A3 and C, LC wave shape of 1.2/50 μs is used to simulate the steepest LC to obtain results in worst cases. The aim of case B is to compare the impact of different location of LC striking, thus intermediate rise time of LC wave shape 8/20 μs is used.

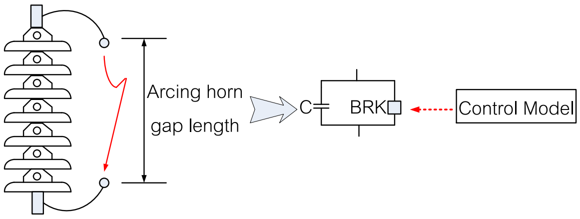

Figure 9 Insulator string and its model

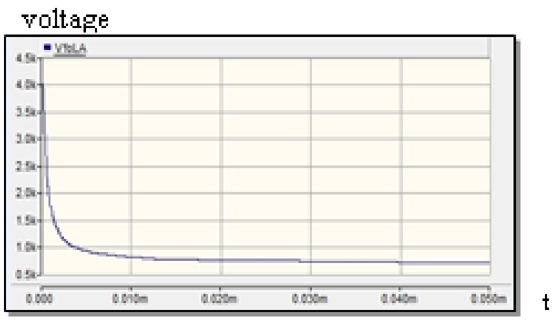

Figure 10 v-t curve

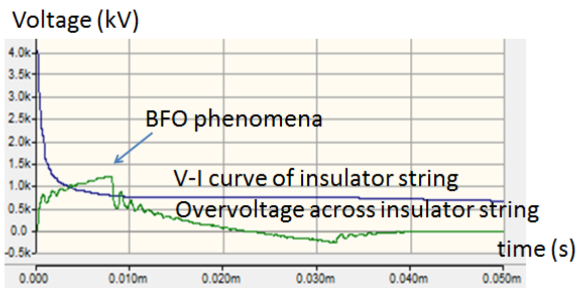

Figure 11 Simulated overvoltage above v-t curve causing BFO

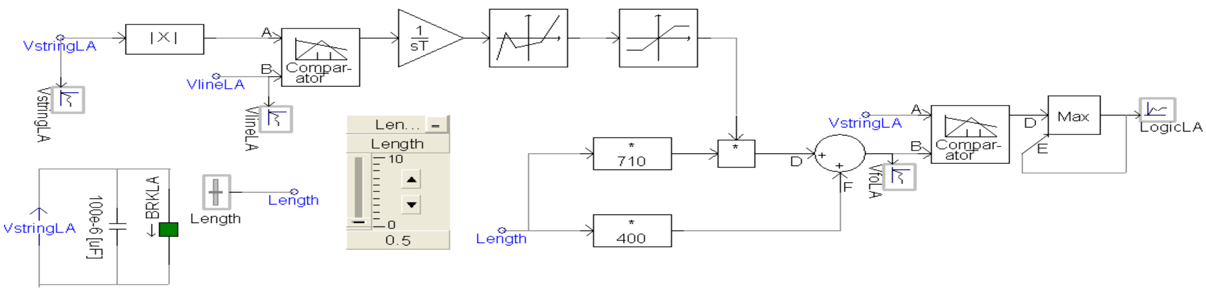

Figure 12 Back flashover logic control

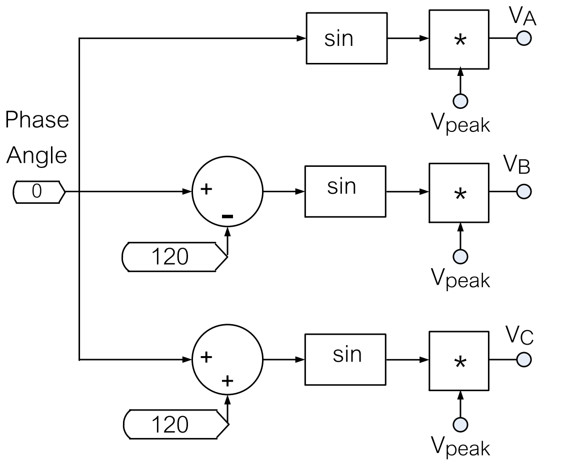

Figure 13 System source model

Table 2 Simulation cases

Cases	Lightning Waveform (μs)	No. of Tower	Source Voltage	Soil Resistivity ($\Omega \cdot m$)	Striking Location
A1	vary	1	no	30	tower
A2	1.2/50	1*	no	30	tower
A3	1.2/50	1	no	vary	tower
B1	8/20	3	no	30	tower/OGW
B2	8/20	3	no	vary	tower
B3	8/20	3	no	vary	OGW
C	1.2/50	3	vary	30	tower

* vary the hight of tower

3.1 Case A

In case A, lightning strikes directly on a single tower without system source voltage as shown in Figure 14. Many parameters are studied in subcases.

Case A1: Different LC magnitude and rise time are studied. The LC magnitude is varied 30–200 kA whereas waveforms are 1.2/50 μs, 8/20 μs and 30/60 μs. Simulation of direct striking at tower type A without system source voltage is performed. Soil resistivity is 30 $\Omega \cdot m$.

The IDV at each tower arm is recorded, the highest IDV occurs at the top tower arm which is selected to demonstrate the effect of lightning waveform shown in Figure 15. IDV could be higher than 6,000 kV in case of 1.2/50 μs LC waveform. The faster rise time of LC induces higher voltage. This can be explained by travelling wave theory. When LC strikes on tower, incident LC wave travels through tower into TFR (Tower Footing Resistance) and dissipate to earth. This produces the corresponding voltage wave travelling in the same direction. At point that tower is bonded with ground rods, LC wave meets different impedance, from high surge impedance of tower to low resistance of TFR. This generates a negative reflecting wave travelling back to the top of tower. When it meets the incident travelling wave, they merge together resulting in the changing point (peak) in the voltage shape, from rising voltage to decreasing voltage as shown in Figure 16. Later on, traveling waves move back and forth. The resulting non-repetitive disorder waveform is obtained from the merging among these travelling waves. Thus, the IDV corresponding to the faster rise time can reach higher point before arriving of the first negative reflecting wave.

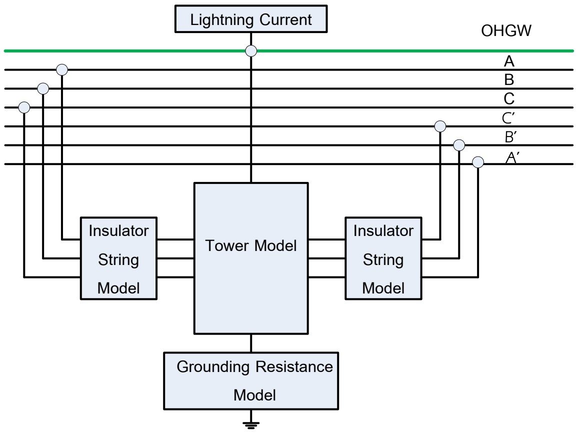

Figure 14 Case A, simulation of lightning strike on one tower

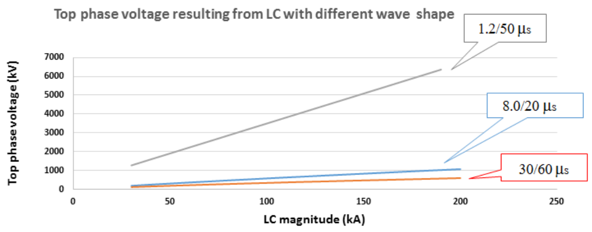

Figure 15 Case A1, comparison of induced voltage due to lightning wave shape at top tower arm

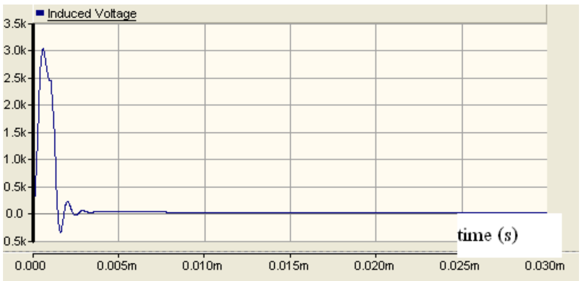

Figure 16 Case A1, induced voltage due to lightning wave shape

Case A2: Different tower height is studied. Four tower types: A, B, C and D, mentioned in Section 2.2, are used in these simulations. The lightning current magnitude is varied 30–200 kA whereas waveform is 8/20 μs. Soil resistivity is 30 $\Omega \cdot \mathrm{m}$. Simulation results show that tower type D experiences the highest IDV whereas the lowest IDV occurs at tower type B shown in Figure 17. Similarly result, IDV at top tower arm is higher than those of middle and bottom tower arm. Therefore BFO at top tower arm occurs easier than middle and bottom tower arm as shown in Figure 18, noted that NFO stands for 'not flashover'.

Case A3: Different soil resistivity is studied. Soil is varied: 30, 100, 150, 300 and 1,000 $\Omega \cdot \mathrm{m}$. The LC magnitude is varied in range 30–200 kA whereas the LC waveform of 1.2/50 μs is constantly used. Simulation results show that high soil resistivity leads to high IDV as shown in Figure 19. This can be explained by traveling wave theory and circuit analysis. The reflection coefficient ($\gamma_{reflect}$) calculated from (14) depending on tower surge impedance (Z_T) and TFR resistance (R_f).The reflection voltage wave is obtained from (15).

$$\gamma_{reflect} = \frac{R_f - Z_T}{R_f + Z_T} \tag{14}$$

$$V_{reflect} = \gamma_{reflect} \cdot V_{incident} \tag{15}$$

The higher soil resistivity will result in higher R_f calculated from (7)-(9). This higher R_f generates a smaller amplitude of reflection wave due to the smaller of difference $R_f - Z_T$ leading to smaller $\gamma_{reflect}$ and smaller negative reflecting wave. When it meets and immerges with incident wave, the higher IDV is obtained. The voltage across R_f is the multiplication of TFR resistance, R_f and LC magnitude. Thus, higher R_f reflects higher voltage.

3.2 Case B

In case B, lightning striking on one of three towers without system source voltage is simulated. The effect of striking location on BFO is studied.

Case B1: Different striking location is studied. Lightning may directly strike on either tower or OHGW as shown in Figure 20 and Figure 21. The soil resistivity is 30 $\Omega \cdot \mathrm{m}$. The lightning current magnitude is varied 30-200 kA whereas waveform of 8/20 μs is constantly used. Simulation results show that lightning striking on tower generates higher IDV than that of striking on OHGW as shown in Figure 22.

Case B2: Different soil resistivity is studied. Lightning directly strikes on tower. The soil resistivity is varied: 30, 100, 150, 300 and 1000 $\Omega \cdot \mathrm{m}$. LC magnitude is varied 30–200 kA whereas waveform of 8/20 μs is constantly used. Simulation results in Figure 23 show that higher soil resistivity leads to BFO easily. For 1,000 $\Omega \cdot \mathrm{m}$ soil resistivity, BFO begins when LC magnitude is 60 kA whereas BFO for 30 $\Omega \cdot \mathrm{m}$ soil resistivity begins at 150 kA LC magnitude.

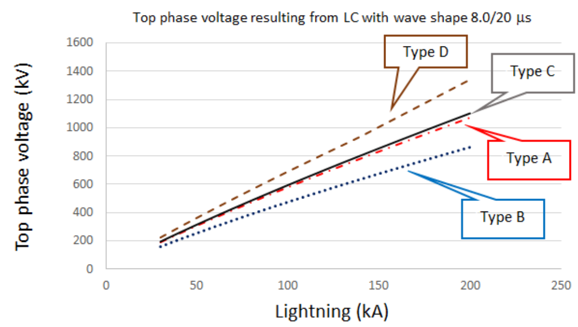

Figure 17 Case A2, comparison of induced voltages at top tower arm due to different tower height

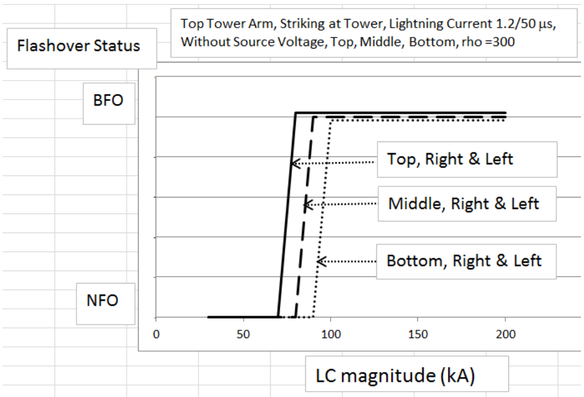

Figure 18 Case A2, comparison flashover status at top, middle and bottom tower arm

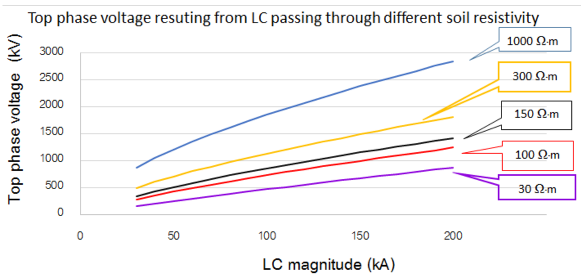

Figure 19 Case A3, comparison of induced voltages at top tower arm due to different soil resistivity

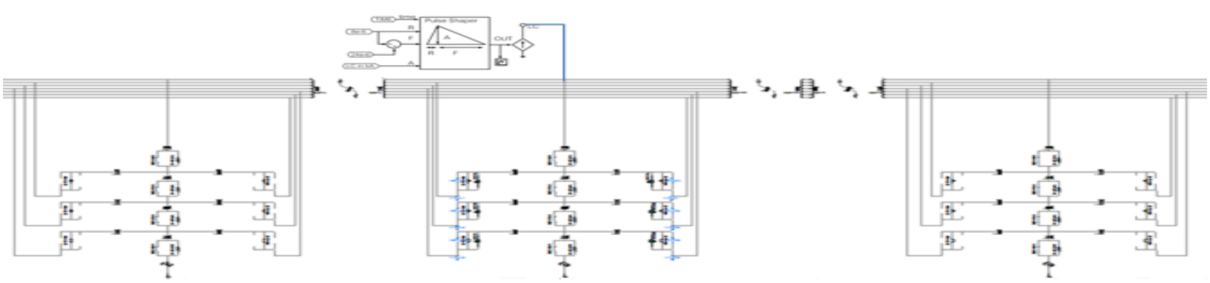

Figure 20 Case B, Simulation of lightning strikes on the middle tower

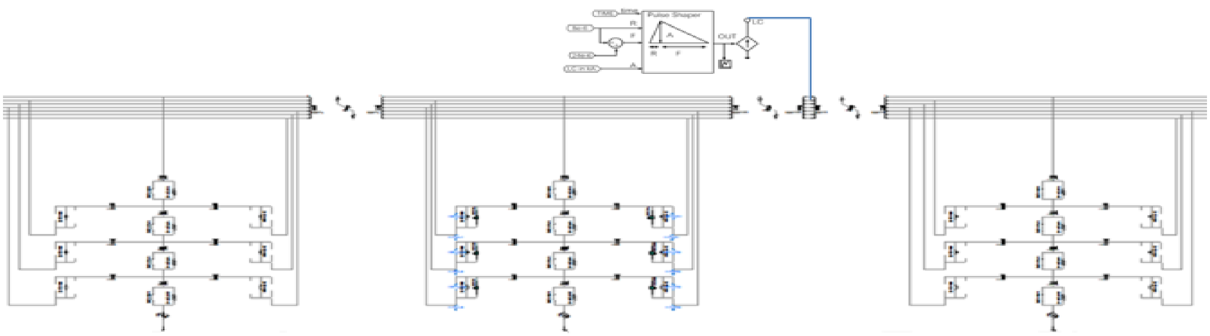

Figure 21 Case B, Simulation of lightning strikes on OHGW

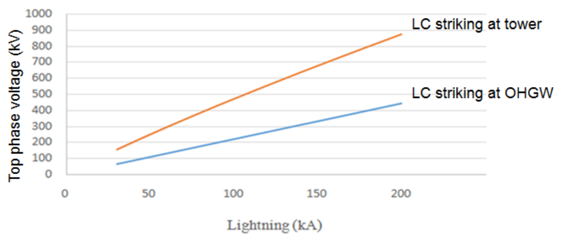

Figure 22 Case B1, comparison of induced voltages at top tower arm due to different location

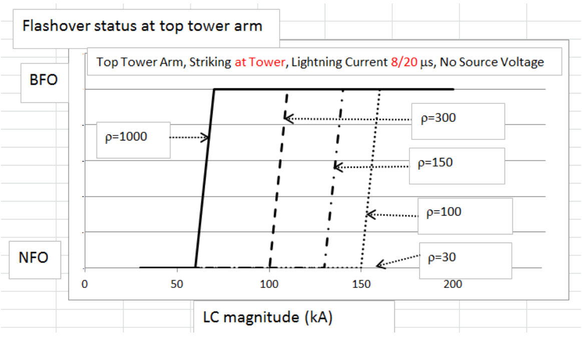

Figure 23 Case B2, comparison flashover status at top tower arm due to different soil resistivity

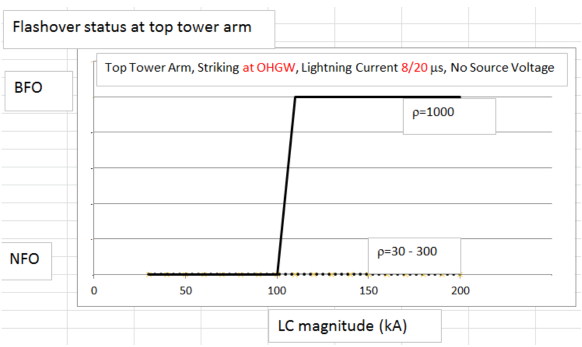

Figure 24 Case B3, comparison flashover status at top tower arm without source voltage, LC 8/20 µs striking at OHGW

Case B3: It is similar to case B2, but lightning directly strikes on OHGW. Simulation results show that lightning striking on OHGW generates lower IDV than that of striking on tower. Thus BFO in case of lightning strike at OHGW can occur only when soil resistivity is 1000 $\Omega\cdot\mathrm{m}$ as shown in Figure 24. There is no BFO in case of soil resistivity 30-300 $\Omega\cdot\mathrm{m}$. However, if LC waveform of 1.2/50 μs is used, BFO may occur.

3.3 Case C

In case C, different of phase angles of source voltage is studied. Lightning directly strikes on the middle tower. The soil resistivity is 30 $\Omega\cdot\mathrm{m}$. The lightning current magnitude is varied 30–200 kA whereas LC waveform of 1.2/50 μs is constantly used. Phase angle is varied: 0º, 30º, 90º, 150º, 210º, 270º and 330º since the highest source voltages occur among three phases as shown in Figure 25. The objective of this case is to compare flashover status at tower arm without source voltage (WO_Source) and with source voltage at different phase angles shown in Figure 25. Simulation results at top, middle and bottom towers are shown in Figure 26 – 28, respectively.

At top tower arm, source voltage with phase angle 270º can cause BFO to occur at higher LC of 100 kA instead of 90 kA in case without source as shown in Figure 26. Whereas source voltage with phase angle 150º, 210º and 270º at the middle tower arm can cause BFO to occur at lower LC of 100 kA instead of 110 kA in case without source as shown in Figure 27. The source voltage with phase angle 90º, 150º and 210º at the lower tower arm can cause BFO to occur at higher LC of 130 kA instead of 120 kA in case without source as shown in Figure 28.

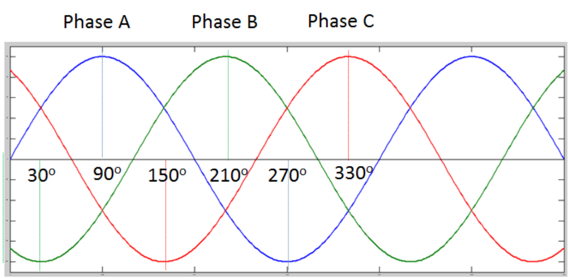

Figure 25 Case C, the polarity and magnitude of each phase at different phase angles

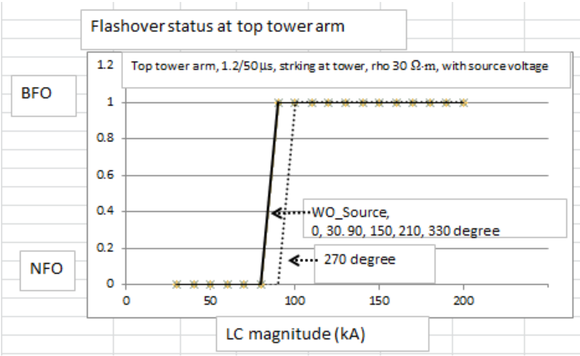

Figure 26 Case C, comparison flashover status at **top** tower arm due to without source voltage and with source voltage at different phase angles

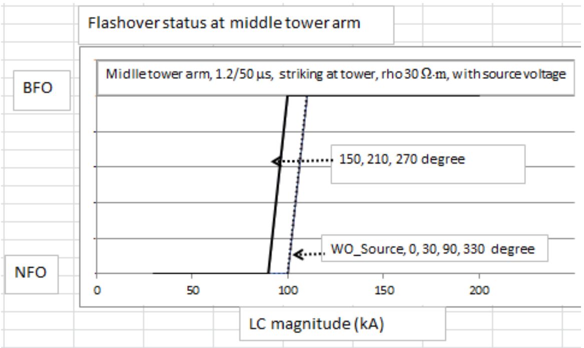

Figure 27 Case C, comparison flashover status at **middle** tower arm due to without source voltage and with source voltage at different phase angles

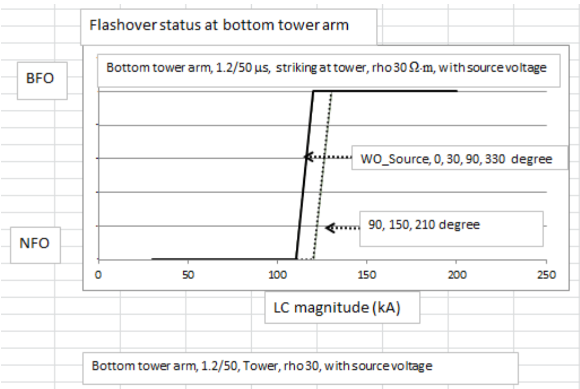

Figure 28 Case C, comparison flashover status at **bottom** tower arm due to without source voltage and with source voltage at different phase angles

4. Discussions

Transmission lines are located in a long distance facing different situations, different soil resistivity and lightning phenomena at each location. In a high mountain, they may face high soil resistivity and high thunder storms. In a drop season, soil is dry resulting in high resistivity. In some cases, the tower must be higher than normal to cross a stream or other obstacles. The mentioned conditions result in higher IDV. In addition, lightning striking directly on the dead end tower generates higher IDV due to the less paths for lightning current to travel. System source voltage may be support or bring down back flashover status depending on the polarity and magnitude of source voltage.

Simulation results show that LC with short rise time and large magnitude can induce very high voltage across insulator string, whereas higher tower and higher soil resistivity can cause higher IDV. In addition, LC striking directly on tower can cause higher IDV than that of striking on OHGW. Thus, the worst case occurs at the top tower arm when LC of 1.2/50 μs with high magnitude directly strikes on tower type A (for 115 kV) located in area with high soil resistivity especially in the first storm after drop season. Furthermore, source voltage may cause BFO to occur easier depending on phase angle during LC striking.

IDV across insulator string simulated by PSCAD was compared with that of TFLASH, software package developed by Electric Power Research Institute (EPRI) in [4].They were mostly the same shape. The voltage shape produced in this paper in Fig. 16 is quite similar to that one in [4], whereas the magnitude of IDV is in the same range as in [4].

5. Conclusion

Simulation results illustrate that the important factors influencing on back flashover phenomena across insulator string are the magnitude and rise time of lightning current, tower footing resistance, the height of tower, location of lightning strike and phase angles of system source voltage. The IDV at the tower arm increases when lightning current is larger or the rise time is shorter. Whereas low TFR affects in a lower IDV leading to a less risk to back flashover. High transmission tower experiences higher IDV. The top tower arms experience higher IDV leading to first priority of back flashover probability. Lightning striking directly on tower induces voltage higher than that of striking on overhead ground wires. Finally, back flashover phenomena at the transmission lines with marginal IDV depends on the phase angle of system source voltage. Engineers can use these findings to analyze back flashover phenomena in transmission lines in different situations and plan to improve tower grounding resistance.

6. Abbreviation

BFO: Back flashover
CB: Circuit breaker
IDV: Induced voltage
LC: Lightning current
NFO: Not flashover
TFR: Tower footing resistance
OHGW: Overhead ground wire

7. References

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