Effective Elimination Factors to the Generated Lightning Flashover in High Voltage Transmission Network

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Abstract: Lightning caused interruptions by shielding failures or by back-flashover. Lightning over voltages cannot be avoided but their influence can be limited by appropriate over voltage protection. In this paper, Characteristics and hazards of lightning overvoltage in the Egyptian Bassous-Cairo West 500-kV transmission line single circuit are analyzed and discussed. Some effective factors, which affecting generated lightning back-flashover across the insulator of a transmission system are analyzed. These factors are included magnitude of lightning stroke, front and tail times of lightning stroke impulse, and chopped current. The influence of connecting Substations Surge Arrester SSA and Line Surge Arrester LSA are investigated. This paper also provides a procedure to limit lightning flashover and back-flashover. ATP-EMTP simulation program is applied to analyze the lightning over-voltage of power line. The result show that there is a 100% probability of an insulator flashover in case high peak, short front time, and any tail time of lightning strokes without any installed arrester. LSA prevent insulator flashover than back flash over.

Keywords: lightning strokes, ATP-EMTP, lightning protection, back flashover, LSA.

1. Introduction
    Power interruptions and economic losses were caused when flashover occurs at lightning over voltage exceed the line insulation strength [1- 3].
    When the humidity reaches a significant level, there will be the appearance of partial discharges on the insulator surface, along with arcs and, finally, there is accelerate flashover of the insulator [4]. The lightning overvoltage is one of an important factors causing flashover, in case direct and indirect lightning strokes, and damage the insulators in the transmission line.
The transient response on the power line must be either accurately analyzed. So in this paper Egyptian Bassous-Cairo West 500-kV single circuit line components model are implemented using Alternating Transient Program ATP_EMTP. Flash over influence in power line are analyzed and discussed. Effective factors on the transient voltage generated across insulator due to direct and indirect lightning are analyzed. This paper also provides a procedure to limit lightning flashover and back-flashover.

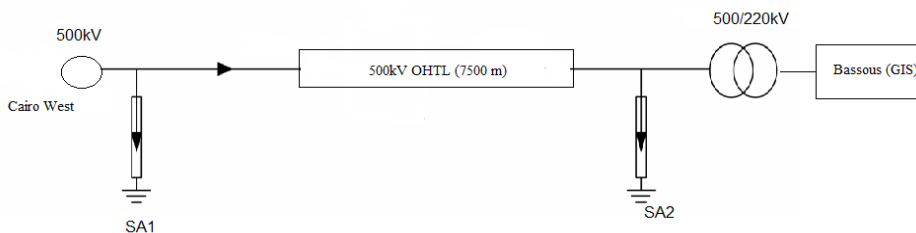## 2. Description and Modeling of the Bassous-Cairo West Power Line.

Figure 1. Single line diagram of Bassous-Cairo West power line

Figure 1 shows single line diagram of Bassous-Cairo West power line. Bassous-Cairo West power line length is 7500 m, transmitted power is 500 MVA, its maximum flowing current is 940 A and its voltage is 500 kV. Its data are summarized in table 1.

Table 1 Bassous-Cairo West

Item	Value
MVA	500
Line voltage (r.m.s) in kV	500
Line Length in km	7.5
Positive & negative sequence impedance per phase	3.307+ j14.053 ohm
Zero sequence impedance per phase	10.75+j45.67 ohm
tower circuits	1
phase sub-conductors	3
ground wires	2
sub-conductor diameter	30.6 mm
phase sub-conductor Spacing	47 cm
Span	400 m
ground wire diameter	11.02 mm

Due to significant influence of lightning strokes, so in this section Bassous-Cairo West power line components is implemented using using ATP-EMTP.

A. Tower and Transmission Line Modeling

Single three phase circuit is carried on its steel tower, as shown in fig 2. Each phase contains three sub-conductors, which are fixed by right angle.
The simulation of the overhead transmission lines was carried out using LCC JMarti model with dimension as in Table.1 [5, 6].
Figure 2 shows the geometry of tower used in this paper. The surge impedance for each part of tower is 200 Ω and the propagation velocity is 2.5 *10^8 m/s [3, 7].
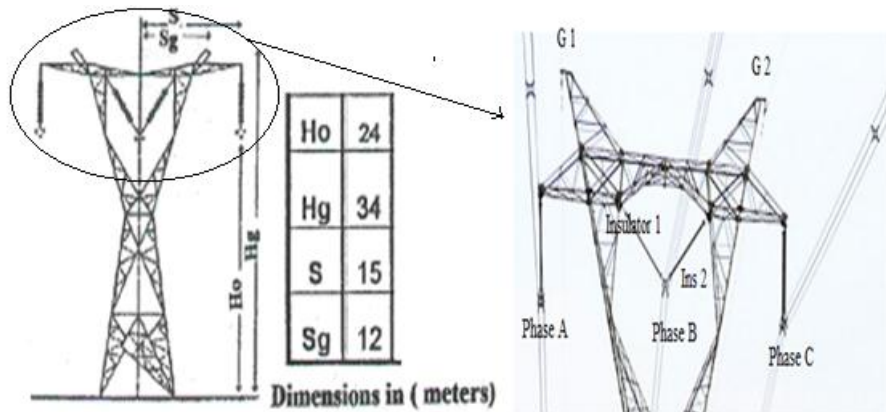

Figure 2. 500 kV transmission tower configuration

The surge impedance of the gantry is 104Ω which calculated according to Eq. (1) as shown in Figure 3[5].

$$Z = \frac{60\ln(h/r) + 90(r/h) + 60\ln(h/b) + 90(b/h) - 120}{2} \tag{1}$$
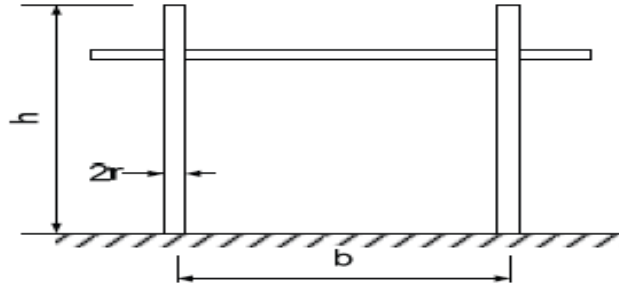
where, r, h, and b lengths (m)

Figure 3. Simplified model of the gantry

B. Earthing System of tower

In this paper, assuming each tower has four legs connected in parallel; each leg is grounded with a vertical rod, the rod has a length of (1.5 m) with radius of (1.25 cm). The soil parameters such as ρ are taken as 100 Ω.m, εr and μr are taken as 10 and 1, respectively [8, 9].
To include high frequency and soil ionization effects [8, 18], the vertical rod model is presented in fig 4 by an R(t)-L-C parameters.
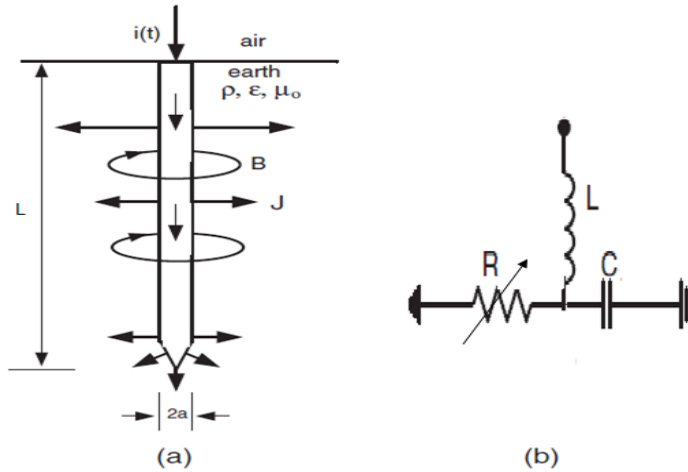

(a)   (b)

Figure 4. Ground rod model. (a) Current flow, (b) equivalent circuit.

The rod parameters are calculated based on the following equations [3, 8, 9, 18]. Where R (t) , C, and L are in Ω, F, and H, respectively, and given by:

$$R(t) = \begin{cases} R_0 \rightarrow For(i < Ig) \\ \dfrac{R_0}{\sqrt{1 + \dfrac{i}{Ig}}} \rightarrow For(i \geq Ig) \end{cases} \quad (2)$$

where, i is the current through the rod (kA), and Ig is the critical current for soil ionization (kA) which is given by:

$$Ig = \frac{E_0 * \rho}{2\pi R_0^{\,2}} \quad (3)$$

where, E_0 is the critical soil ionization gradient (in this study is taken as 300 kV/m as a case study). The constant resistance R_o (ohm) of the model is based on the rod dimensions and the soil parameters [9, 18]:

$$R_0 = \frac{\rho}{2\pi d} \{\ln\frac{4l}{a} - 1\} \tag{4}$$

$$C = \frac{\rho\varepsilon}{R_0} \tag{5}$$

$$L = 2l * 10^{-7} * \{\ln\frac{2l}{a} - 1\} \tag{6}$$

where, ρ is the soil resistivity (Ω.m), L is the electrode length (m) and a is the electrode radius (m).

The horizontal grounding conductor circuit is shown in Figure 5 and these parameters are derived from Sunde's formulas [10, 11].
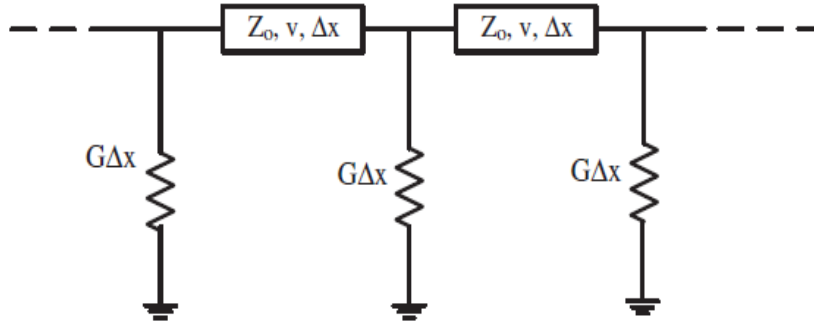

Figure 5. Horizontal conductor

C. Line Insulator String and Flash over Modeling

A clean insulator consists of a linear resistor R and capacitor C in parallel, having a total equivalent capacitance of 3.94 pF [7] and equivalent resistance 4421 MΩ [12] was used as shown in fig 6.
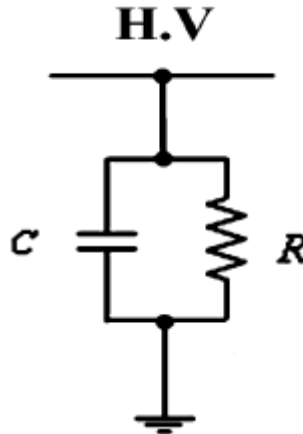

Figure 6. Insulator equivalent circuit

Lightning impulse withstand voltage level of the insulator string is not a unique number [3, 13, 18].

The simplest approach for the representation of the back flashover is to model as parallel switch across the insulator, which closes when the voltage exceeds a defined limit determined by Eq.(7) .

For 500kV insulator string, Flashover voltage (V_{fo}) is calculated from Eq.(7) depending on elapsed time (t).

$$V_{fo} = (400 + \frac{710}{t^{0.75}}) * L \qquad (7)$$

Where V_{fo} is flashover voltage, kV, L is the insulator string length, m, and t is elapsed time after lightning stroke in μs.

D. Lightning Stroke and Surge Arrester Modeling

Heidler current function model is widely used to model a lightning, Eq. (8) [3, 4]. A 400 Ω lightning channel was used as shown in fig 7.

$$i(t) = I_o \frac{(t/\tau_1)^2}{[(t/\tau_1)^2 + 1]} e^{-t/\tau_2} \qquad (8)$$

where I_0: the peak of current, τ_1, τ_2 : current rising and dropping time constants.
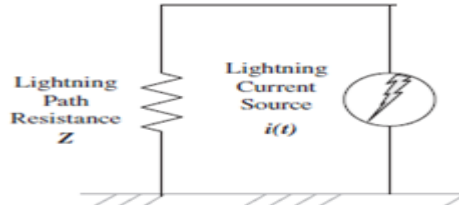

Figure 7. Lightning current model.

In this paper, the selected arrester 318 kV/rms (MCOV) of arresters with L1 and L0 equal 21.75μH, and 0.29 μH. A simplified parameter model of surge arrester was derived from IEEE model [15]. The selected model circuit is shown in fig 8 [14, 15, 16].
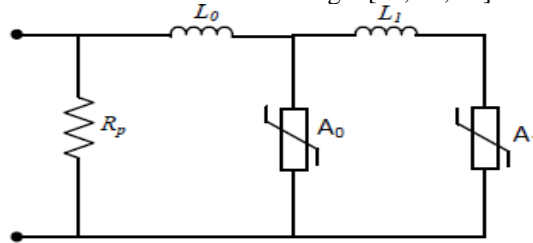

Figure 8. Pinceti and giannettoni model

3. Results and Discussion

Including gantry total nineteen towers, 500kV single circuit with two overhead ground wire, are represented in the simulation model. The phase conductor and ground wire are explicitly modeled between the towers; Fig 9 shows the span of eighteen towers (M1 to M18) between Cairo West/Bassous substations. The lightning stroke is taken as striking top of tower M9 connected shield wire G1 which near midpoint of transmission line as shown in figure 9.
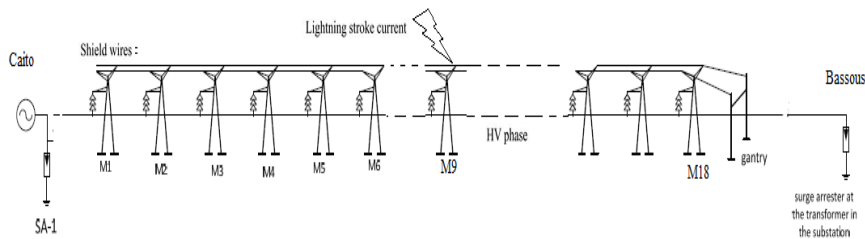

Figure 9. Model of 500 kV line

Figures 10 (a) and 10 (b) show the voltages across insulator strings of phases under normal operation and lightning stroke hit G1. The lightning impulse is assumed to have the following parameters: peak value of 100 kA, front time equals 1 μs and tail time equals 50 μs [17].

It is observed that in (figure 10 a) the (M9) voltage across insulators in normal line voltage reach to about 408 kV, this value of peak phase voltage.
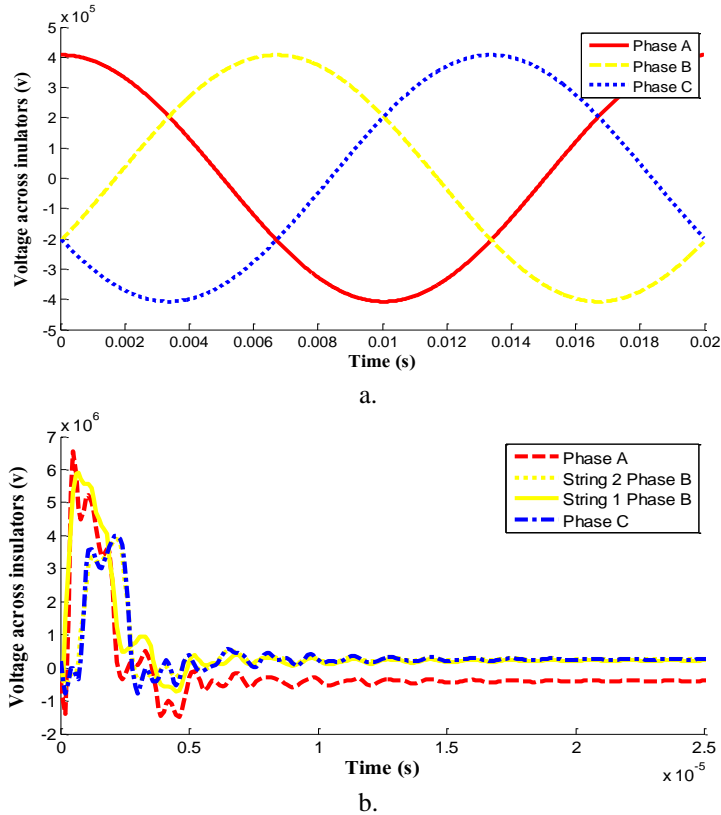

a.

b.

Figure 10. Voltage waveforms on different phases string insulator: (a) under normal operation, (b) under 100kA lightning strokes.

In case of without using flashover model, fig 10 (b) shows voltage across insulator, voltage difference between tower point and phase A point, reaches to 6.5 MV at (M9) phase (A) insulator string, 6 MV at (M9) string 1 of phase (b) insulator string, 4 MV at (M9) string 2 of phase (b) insulator string, and 4 MV at (M9) phase (c) insulator string.

It is noticed that the lightning suffers the most severe overvoltage at insulator string of phase (A), which indicates that the insulator string of phase (A) is most likely to back flashover first, Phase (A) is located near the G1 which hit by lightning strokes than phase (B and C) as shown in figure 3.

A. Effect of Different Lightning Current Peak

Figure 11 shows the voltage across phase A insulator string waveform comparison at M9 tower, at different peak values of lightning stroke (20, 30, 40 and 50 kA, 1.2/50 μs) hit G1. The result shows the voltage across phase A insulator string reach to 1 MV under 20kA lightning strokes, 1.8 MV under 30kA lightning strokes, 2.3 MV under 40kA lightning strokes, and 3 MV then reach to zero under 50kA lightning strokes. It is noticed that the magnitude of the voltage across phase A insulator string increases with the increasing the peak of lightning current. On other hand the 50kA lightning stroke is the minimum lightning peak to make back

flashover in phase A insulator string occurs, At 50kA strokes the Volt-time curve intersects the voltage curve lead to insulator back flashover.
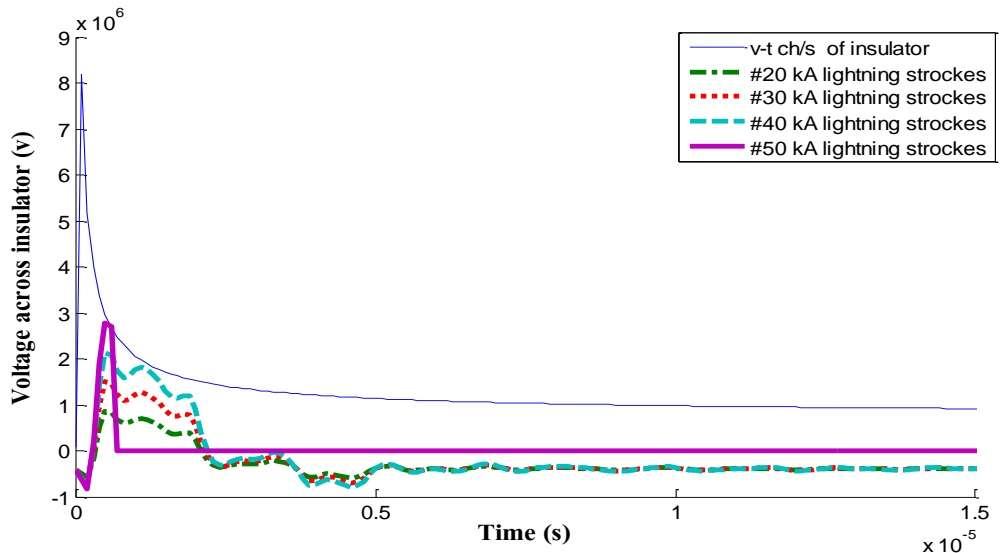

Figure 11. Voltage across phase A insulator string comparison at different peak values of lightning stroke (20, 30, 40 and 50 kA, 1.2/50 µs)

B. Effect of Different Front Time of Lightning Current

Figure 12 compares voltage across phase A insulator string waveform with various front time of lightning strokes; 2, 5, 6, and 7µs[3], with magnitude 50 kA hit G1 at tower M9. It is observed that the shorter front wave time increases the voltage across phase A insulator string. It is noticed that the 5µs front time of lightning strokes is the minimum front time to make back flashover in phase A insulator string occurs, At 2, and 5µs front time of lightning strokes the Volt-time curve intersects the voltage curve lead to insulator back flashover, Also the shorter front time make back flashover insulator string occurs faster than others.
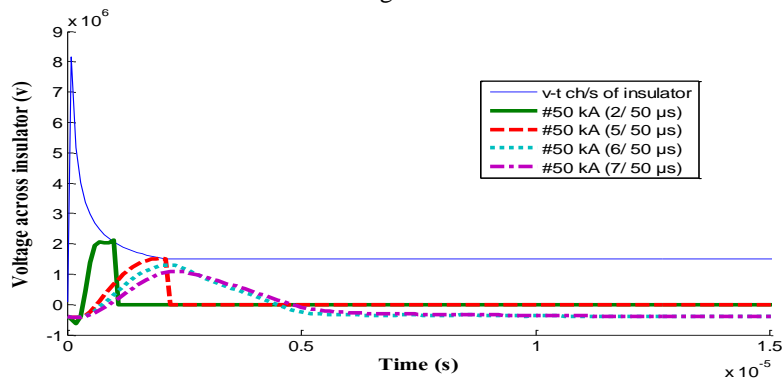

Figure 12. Voltage across phase A insulator string comparison at various front time of lightning strokes

C. Effect of Different Tail Time of Lightning Current

Figure 13 compares voltage across phase A insulator string waveform with various tail time of lightning strokes; 10, 50, 80, and 100µs, with magnitude 50 kA hit G1 at tower M9. It is seen that the longer tail wave time increases the voltage across phase A insulator string. It is noticed that the at various tail time of lightning strokes the Volt-time curve intersects the

voltage curve lead to insulator back flashover, on other hand the longer tail time make back flashover insulator string occurs faster than others.
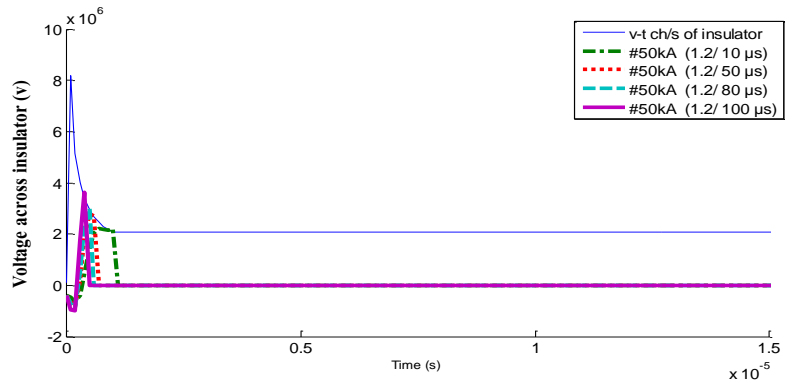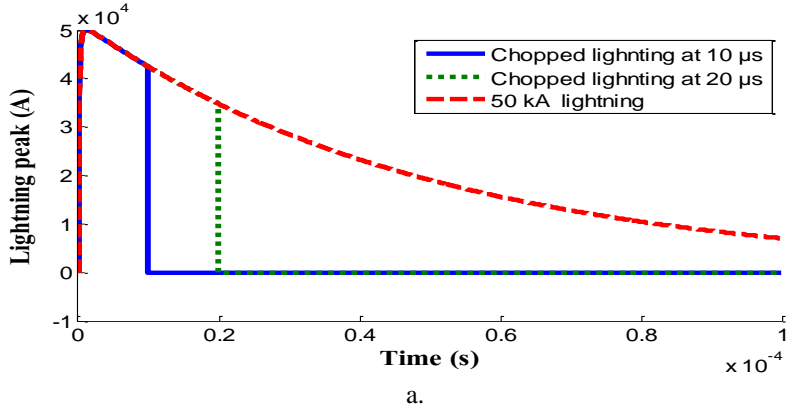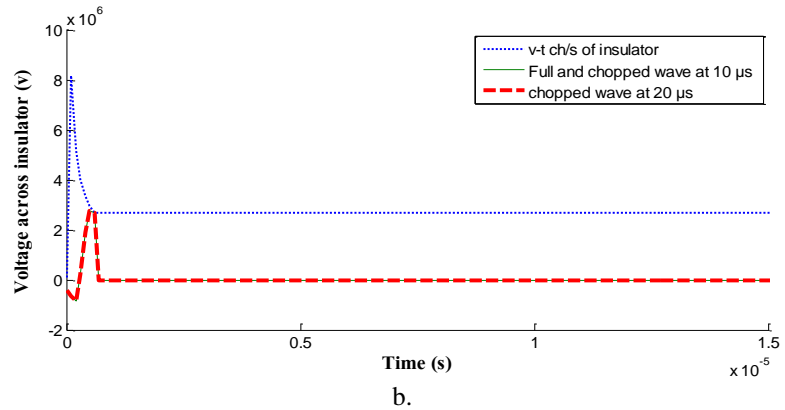

Figure 13. Voltage across phase A insulator string comparison at various tail time of lightning strokes

D. Effect of Different Chopped Tail Time of Lightning Current

Figure 14(a) shows complete lightning stroke and others chopped at tail time 10, and 20 µs waveforms used in this case study. It is noticed that the chopped wave has no effect on the voltage across phase A insulator string as shown in figure 14(b).

a.

b.

Figure 14a. Different lightning waveform

b. Voltage across phase A insulator string comparison at various lightning strokes

E. Effect of Shield Failure

With effective shielding, it is possible to minimize direct strokes to the phase conductors, but this does not necessarily mean that the line will have satisfactory lightning performance. A shielding failure or a stroke to the conductor is essentially a single-phase.

Figures 15 (a) and 15 (b) show the voltages across phase A insulator string under lightning stroke hit directly phase A and lightning stroke hit G1 at tower M9 with and without using flashover model, 50kA (1.2/50 μs),.

It is observed that in (figure 15 a) the voltage across insulator in case direct lightning stocks, voltage difference between phase point and tower point, and indirect lightning stocks, voltage difference between tower point and phase point, reach to about 8.5MV and 3MV, respectively.

With using flashover model, figure 15 (b) show the voltage across phase A insulator string intersects Volt-time curve, which lead to insulator *flashover* and *back flashover* in case direct and indirect lightning strokes, respectively. It is noticed that the *flashover* more serious and occurs faster than *back flashover*.
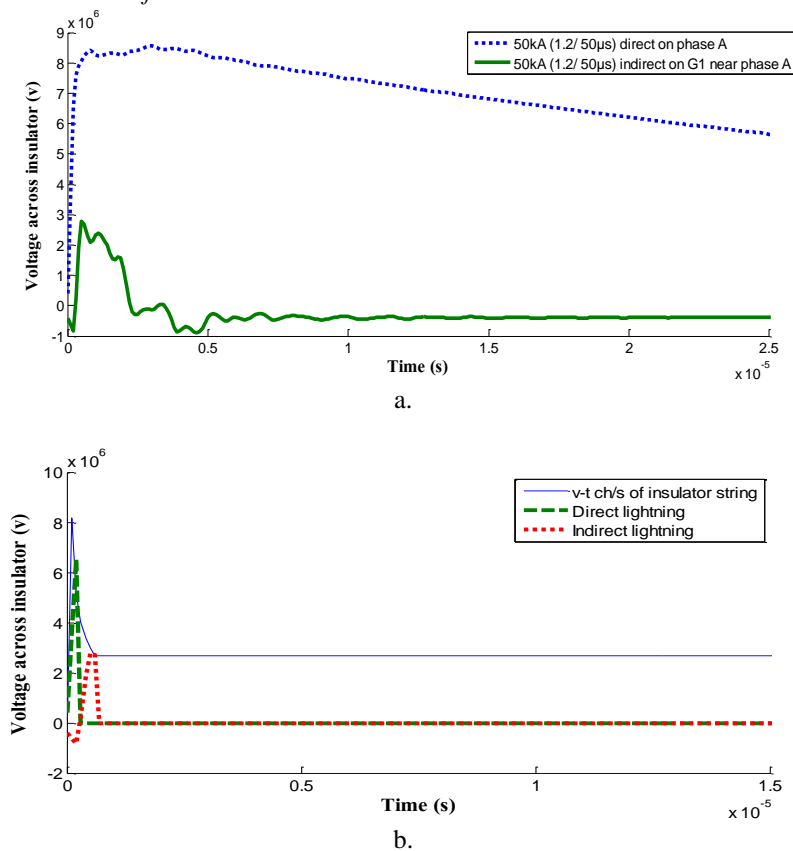

a.

b.

Figure 15. Voltage across phase A insulator string comparison at direct and indirect lightning strokes (a) Without using flashover model (b) With using flashover model

4 . Flashover and Back flashover Mitigating Technique.

A. Effect of Substation Surge arrester (SSA)

In this section the effect of SSAs installed at entrance of Cairo west and Bassous substations on *flashover*, produced by direct lightning stroke, and *back flashover*, produced by indirect lightning stroke, analyzed.

A.1. Effect on Back flashover

Figures 16 (a) and 16 (b) show the (M9) phase A voltage and (M9) voltage across phase A insulator string under lightning stroke,50kA (1.2/50 μs), hit G1 at tower M9 with and without using SSAs. The result show that in (fig 16 a) the (M9) phase A voltage reach to about 2.8MV and 2.5MV with and without using SSAs, respectively.

Figure 16 (b) compares (M9) voltage across phase A insulator string waveform with and without using SSAs. It is noticed that the installed SSAs reduce phase voltage, but has no effect on *back flashover*
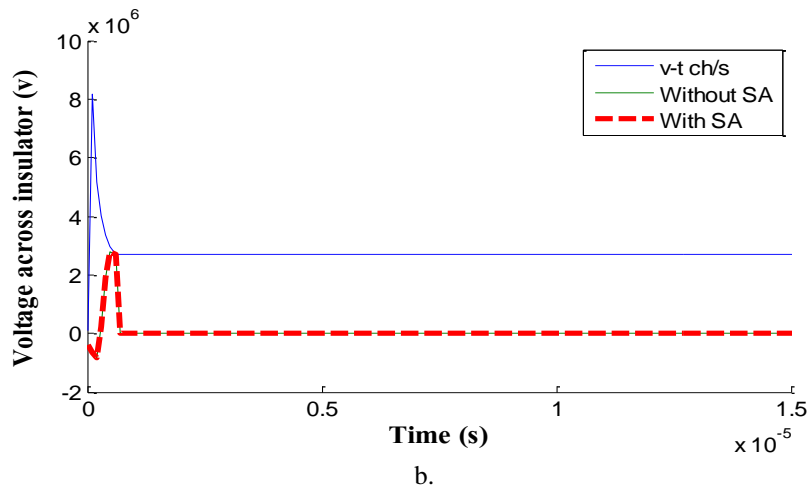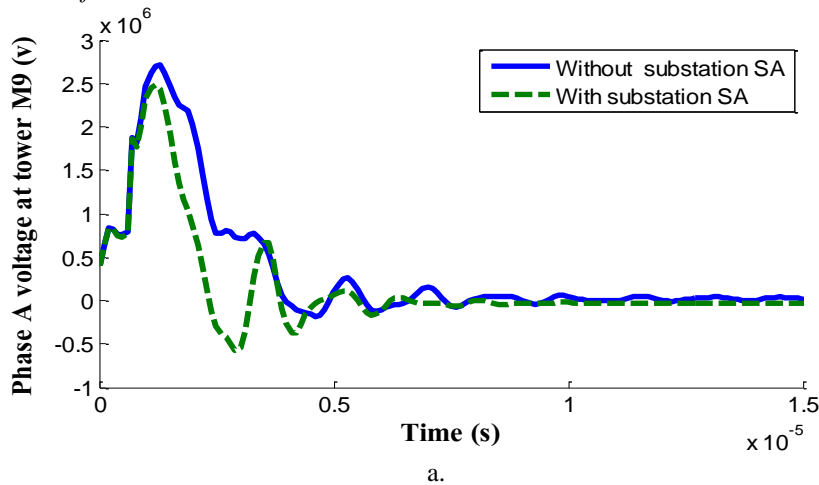

a.

b.

Figure 16. With and without using SSAs under lightning stroke hit G1 at tower M9, (a) (M9) phase A voltage waveforms, (b) (M9) voltage across phase A insulator string

A.2. Effect on flashover

Figures 17 (a) and 17 (b) show the (M9) phase A voltage and (M9) voltage across phase A insulator string under lightning stroke,50kA (1.2/50 μs), hit phase A at tower M9 with and without using SSAs. The result seen that in (fig 16 a) the (M9) phase A voltage reach to about 6.5MV and 2.5MV with and without using SSAs, respectively.

Figure 17 (b) compares (M9) voltage across phase A insulator string waveform with and without using SSAs. It is noticed that the installed SSAs has greatly reduce voltage across insulator but not completely eliminate the flashover.
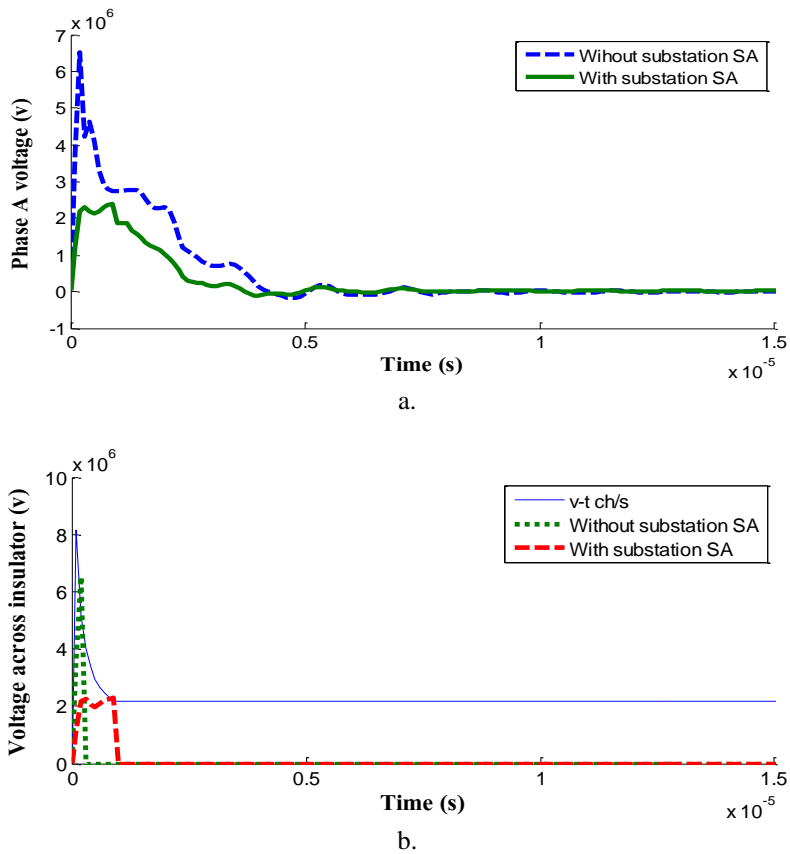
a.

b.

Figure 17. With and without using SSAs under lightning stroke hit phase A at tower M9, (a)
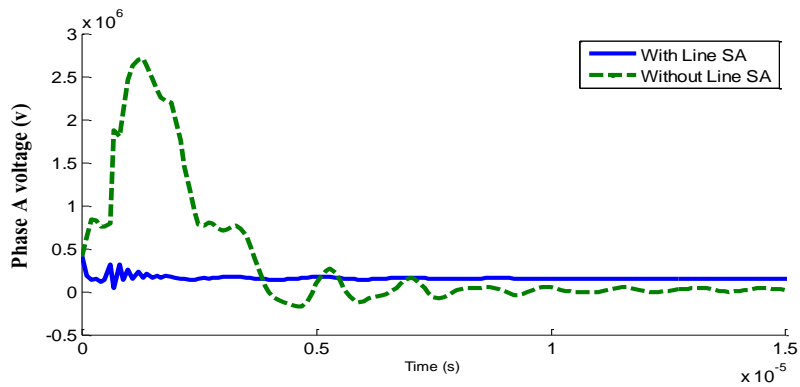(M9) phase A voltage waveforms, (b) (M9) voltage across phase A insulator string

B. Effect of Line Surge Arrester (LSA)

In this section the effect of LSA installed in parallel with insulator string on *flashover*, produced by direct lightning stroke, and *back flashover*, produced by indirect lightning stroke, analyzed.
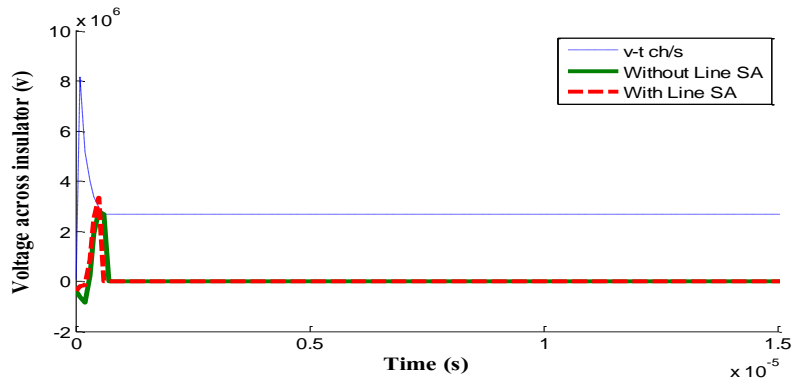
B.1. Effect on Back flashover

Figures 18 (a) and 18 (b) show the (M9) phase A voltage and (M9) voltage across phase A insulator string under lightning stroke,50kA (1.2/50 µs), hit G1 at tower M9 with and without using LSAs. It's seen that in (fig 18 a) the (M9) phase A voltage reach to about 2.8MV and 408kV with and without using LSA, respectively.

Figure 18 (b) compares (M9) voltage across phase A insulator string waveform with and without using LSA. It is noticed that the installed LSA can accelerate *back flashover* due to circulating current result in LSA.
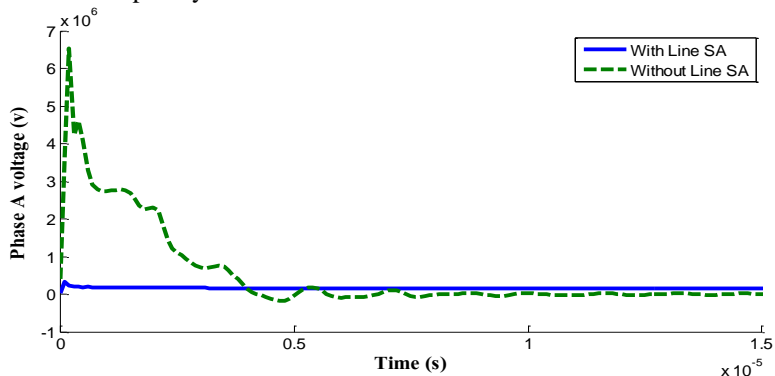
a.

b.

Figure 18. With and without using LSA under lightning stroke hit G1 at tower M9, (a) (M9) phase A voltage waveforms, (b) (M9) voltage across phase A insulator string

B.2. Effect on flashover

Figures 19 (a) and 19 (b) show the (M9) phase A voltage and (M9) voltage across phase A insulator string under lightning stroke ,50kA (1.2/50 μs), hit phase A at tower M9 with and without using LSA. The result show that in (fig 16 a) the (M9) phase A voltage reach to about 6.5MV and 408kV with and without using LSAs, respectively.

Figure 19(b) compares (M9) voltage across phase A insulator string waveform with and without using LSA. It is noticed that the installed LSA has greatly reduce voltage across insulator and completely eliminate the flashover.
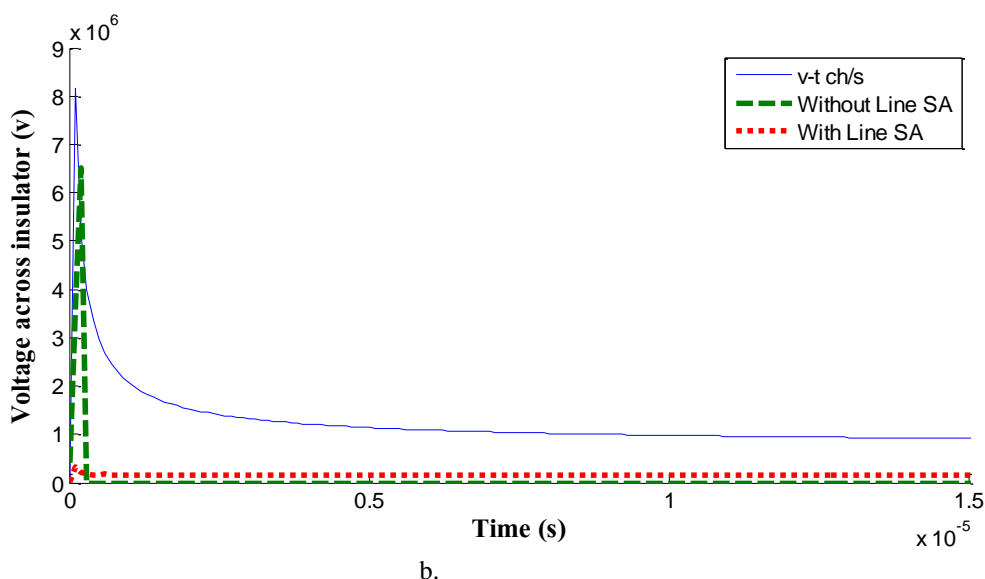

a.

b.

Figure 19. With and without using LSA under lightning stroke hit phase A at tower M9, (a) (M9) phase A voltage waveforms, (b) (M9) voltage across phase A insulator string

5. Conclusions

In this work, the effect of direct and indirect lightning impulse on probability of flashover occurrence in insulator string is analyzed using the related equivalent circuit by using ATP-EMTP. Several factors may contribute to a back flashover due to lightning strokes including, magnitude of lightning stroke, front and tail times of lightning stroke impulse, and chopped current. The influence of connecting Substations Surge Arrester SSA and Line Surge Arrester LSA are investigated. As seen from the simulation results, the voltage magnitude across insulator increases with the increase peak of lightning current. Lightning stroke peak above 50kA make occurrences of back flashover probability increase. Also it is observed that the shorter front wave time increases the voltage across insulator string. Front time of lightning strokes less than 5μs increase probability of back flashover occurrences. No great effect of tail time and chopped wave.

Finally, Installed LSA or SSAs reduce phase voltage. If no arresters are installed on a line there is a 100% probability of an insulator flashover. if LSA are installed on phase of tower, a direct strike phase conductor will result in 0% probability of an insulator flashover and a 100% probability of an insulator back flashover in case lightning hit shield wire.

However, it still has other important factor, tower footing resistance, to consider reducing the back flashover for transmission line.

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