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The Influence of Lightning and Grounding Conditions On Flashover Events in a 150 kV Transmission Line

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Abstract— Effect of lightning parameters and grounding system impedance on transient overvoltage that occurs in 150 kV overhead transmission lines during lightning using ATP-EMTP modeling. The induced overvoltage that jumps across the insulator is calculated for further analysis. Various parameters that directly influencedirectly influence the backflashover phenomenon,, such as the effect of lightning strike amplitude, time of rise (front) and decay (tail) of lightning impulses, foot grounding system, and ground resistivity,, are discussed in more detail. Surge arresters are used in this study to overcome the overvoltage that can cause backflashover. The performance of the transmission system after using a surge arrester is investigated at the time of a lightning strike. The results indicate that the parameters of the advance time and the lightning current amplitude greatly affect the overvoltage magnitudeoltage. Other parameters have little effect on the overvoltage in the transmission line.

Keywords: Front Time, Tail Time, Back Flashover, Overvoltage, Component, Lightning, and Surge Arrester.

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1. Introduction

Lightning strikes can cause damage to the insulator, causing a flashover phenomenon that spreads along the transmission line insulator. Generally, lightning strikes occur repeatedly according to the number and direction of the flow of charge, usually from the cloud to the earth, and occur more than once, known as a return stroke. Early strokes are generally more dangerous than subsequent strokes [1].

Damage to electrical power equipment components by lightning strikes occurs in the following ways. The first method is to increase the voltage on the equipment, such as impulse voltage, through the insolation ofipment, wh, whichrt circuit disturbance due to flashover [2]. Back flashover is one of several phenomena that can derail the performance and reliability of a transmission line.

The back flashover phenomenon occurs when the voltage impulse exceeds the insulator's dielectric strength andinsulator's dielectric strength and the flashover critical line [3]. The effect of the transmission line protective ground wire during a lightning strike contributes to the lightning-induced voltage, closely related to the grounding impedance of the tower leg. Meanwhile, the foot tower impedance is affected by the ground conductivity (r) and the lightning strike distance (d) [4]. A good lightning protection and grounding system can minimize damage due to lightning strikes [5]. The second method is when the energy of the lightning strike exceeds the ability of the equipment to receive energy; this can cause excess heat and cracks or can further destroy the equipment itself [6]. Lightning parameters directly affecting equipment damage are the characteristics of advance time, tail time, peak lightning current, tower geometry, tower foot grounding impedance, and corona. This paper reports and summarizes the effect of lightning parameters and grounding impedance that affect the performance of lightning strikes when striking the transmission line ground wire and the role of arresters as protective equipment. This study further investigated a 150 kV Sumatera single-circuit transmission line. The effect of direct lightning strikes on high-voltage transmission lines was also included by investigating before and after using surge arresters.

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2. Power System and Modelling

The 150 kV Sumatera transmission system has a double circuit with two ground wires. This research us,es aThis research uses a a single circuit with one ground wire and two bundles of conductors per phase. The configuration of the the proposed tower is illustrated in Figure 1. The space between each phase is 13.2 m,, and the span distance between towers is kept at 300 m [6, 7]. The model of theThe model the transmission tower is shown in Figure 2 (a) and (b).

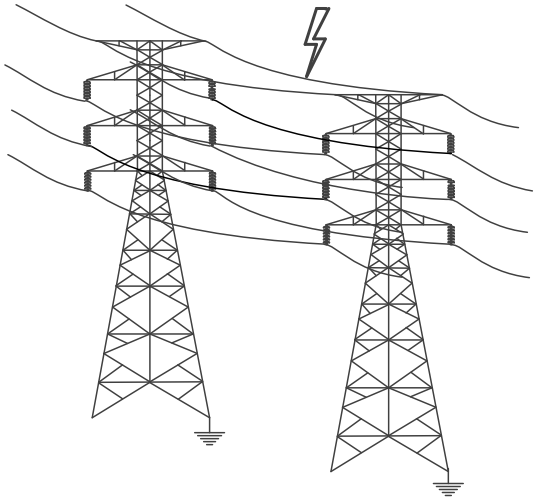
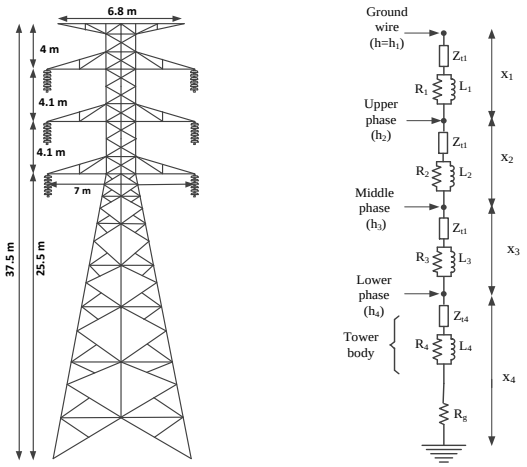


Figure 1. Typical of 150 kV transmission towers



(a) (b)

Figure 2. (a) Transmission Tower of 150 kV system, (b) ATP-EMTP Tower Model

The transmission line is modeled as a line/cable lumped transposed Clarke (LCC),, where this model requires data from positive and zero sequences in the form of resistance, inductance,, and capacitance. Positive and zero sequence resistances can be directly extracted from the data by converting them intointo meters unitsunits. The positive and zero sequence inductance and capacitance value can be calculated using equations (1) and (2) by entering the inductive reactance and capacitive data values in Table II.

$$L_{1,0} = \frac{X_{L1,0}}{2\pi f} \tag{1}$$

$$C_{1,0} = \frac{1}{2\pi f \frac{1}{B_{1,0}}} \quad (2)$$

The transmission line parameters can be seen in Table I. This data is for a 150kV transmission line.

Table 1. Transmission Line Parameters

No.	Parameter	Specification
1	Voltage	150 kV
2	Nominal Current	645 A
3	Number of Circuit	2
4	Conductor Type	HAWK
5	Conductor Diameters	240 mm
6	Power	167,58 MVA
7	Positive Impedances	R = 0.117 Ω/km X = 0.401 Ω/km B = 2.859 µS/km
8	Zero Impedances	R = 0.614 Ω/km X = 1,793 Ω/km B = 1.223 µS/km

Table 2. Converted Field Data to Simulation Data Needed

No.	Parameter	Data Convert for ATP/EMTP
1	R_1 = 0.117 Ω/km	R_1 = 0.000117 Ω/m
2	X_1 = 0.401 Ω/km	L_1 = 0.001277 mH/m
3	B_1 = 2.859 µS/km	C_1 = 9x10^{-6} µF/m
4	R_2 = 0.614 Ω/km	R_2 = 0.000614 Ω/m
5	X_2 = 1,793 Ω/km	L_2 = 0.00571 mH/m
6	B_2 = 1.223 µS/km	C_2 = 3.89x10^{-6} µF/m

Specification of 150kV rated ZnO arrester is shown in Table III. The arrester model used in this study is the model recommended by the IEEE Working Group,, shown in Figure 3. When lightning strikes with a fast front time, the filter impedance becomes more significant. For a 150kV operating system, the rated operating voltage of the surge arrester becomesbecomes 150 kV x √2/√3 = 122.474 kV,, and for the other parameters L_0 = 0.267 µH, L_1 = 19.95 µH, R_0 = 133 Ω, R_1 = 86.45 Ω, and C = 75.20 pF. The characteristics of the voltage and current that interpret the non-linear components are obtained using two non-linear resistors (tagged A0 and A1) separated by RL filters. TheThe filter impedance is very low for slow impulse,, for slow impulse, and A0 and A1 are practically connected in parallel.

Table 3. Specification of 150kV Arrester

No.	Parameter	Data
1	Rated Voltage	150 kV

2	MCOV	120 kV	
3	Max. Residual Voltage (8/20 µs)	5 kA 10 kA 20 kA	367 kV 396 kV 449 kV
4	Height	1.33 m	
5	Insulation Material	Porcelain	
6	Creepage	3.32 m	
7	Energy Capability	8 kJ/kV	

Figure 3 shows the IEEE ArresterArrester model used in this simulation. The model consists of resistance, capacitance, inductance, and two nonlinear components.

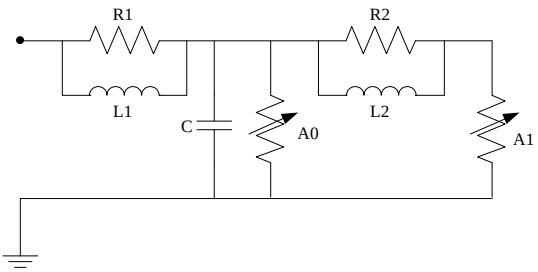


Figure 3. IEEE Arrester Model

The excellent performance of the arresters for protection is supported by the non-linear resistance volt-ampere characteristics in zinc oxide [8-11]. Station class arresters are mainly used in 150 kV transmission systems. Volt-ampere characteristics of non-linear elements A0 and A1 are shown in Figure 4.

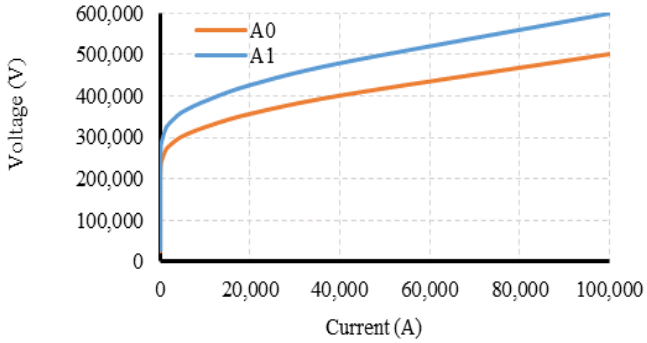


Figure 4. Voltage Current Characteristics of A_0 and A_1

To simulate the the behavior of differentdifferent grounding systemssystems, the model in ATP during lightning transient is shownis shown in Figure 5.

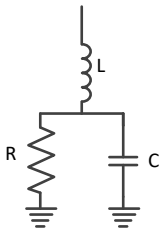


Figure 5. Grounding Model

Resistance, capacitance,, and inductance of grounding parameters model can be obtainedobtained using (3), (4), and (5) respectively [12].

$$R = \frac{\rho}{2\pi l}\left[ln\left(\frac{4l}{a}\right) - 1\right] \ \Omega \tag{3}$$

$$C = 2\pi\varepsilon l.\left[ln\left(\frac{4l}{a}\right) - 1\right]^{-1} \ F \tag{4}$$

$$L = \frac{\mu_0 l}{2\pi}\left[ln\left(\frac{2l}{a} - 1\right)\right] \ H \tag{5}$$

Where a is the radius, and *l* is the length of the electrode. The parameters *ρ, ε,,* and *μ* are, respectively, the soil resistivity, the electrical permittivity of the soil,, and the magnetic permeability of the vacuum. The parameters used in the proposed earthing system model are presented in Table IV for cases 1, 2, 3, and 4.

Table 4. Variation of tower grounding

Grounding Type	R (Ω)	L (H)	C(nF)
1	53.76	2.26	10.82
2	30.32	5.18	24.42
3	16.88	11.71	54.41
4	10.5	15.87	67.89

3. Lightning Model

Lightning impulses current in ATP-EMTP software is modeled as the form of current sources parallel with resistance, represented as lightning path impedance. The lightning path impedance was chosen as 400 ohms [13]. The lightning current model follows (6) developed by Heidler [14, 15]. This lightning impulse model is used as a lightning source in this study [5], where four significant magnitudes of lightning current at the strike point must be considered: rise time, tail time, tower leg impedance, and peak current lightning current [16].

$$i_h(t) = \frac{I_0}{\eta} x \frac{\left(\frac{t}{\tau_1}\right)^{n_h}}{1 + \left(\frac{t}{\tau_1}\right)^{n_h}} e^{-\frac{t}{\tau_2}} \tag{6}$$

Where:

I_0 = Peak current (A)
η = Correction factor of peak current
τ_1 = Rise time (s)
τ_2 = Tail time (s)
n_h = Approximation steepness factor

Modifying these properties gives the desired lightning current waveform. The shape of the lightning current with a rise time of 1.2 us and a tail time of 50 us with an amplitude of 20kA is shown in Figure 6.

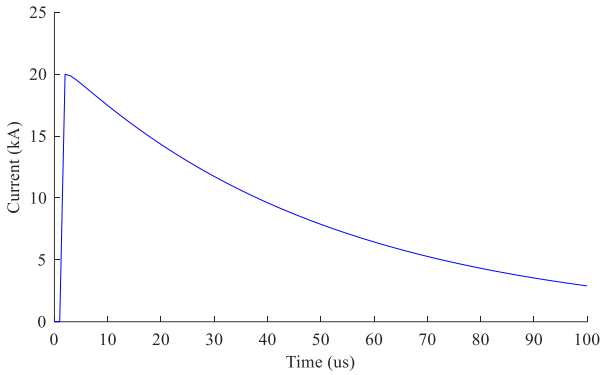


Figure 6. Lightning current characteristic 1.2/50us amplitude 20kA

4. Back Flashover Model

Back flashover occurs when lightning strikes the ground wire or directly above the transmission tower. The current flows into the ground through the tower and runs out to the ground. If the impedance of the tower foot is high, then excess voltage will build up across the line insulator. As a result, if the voltage is equal to or exceeds the critical flashover voltage (CFO), there will be a current jump known as a flashover and then a reverse flashover that occurs in the flashover path on the insulator [5, 13]. The back flashover is modeled electrically with a parallel switch with a phase isolator [16]. This switch has specific volt-time characteristics to be modeled and controlled as in the following equation [17, 18]. The flashover voltage of 160kV insulator is shown in Figure7.

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$$V_{fo} = K_1 + \frac{K_2}{t^{0.75}} \tag{7}$$

where:

$K_1 = 400L$

$K_2 = 710L$

L = arrester length (m)

t = lightning duration (s)

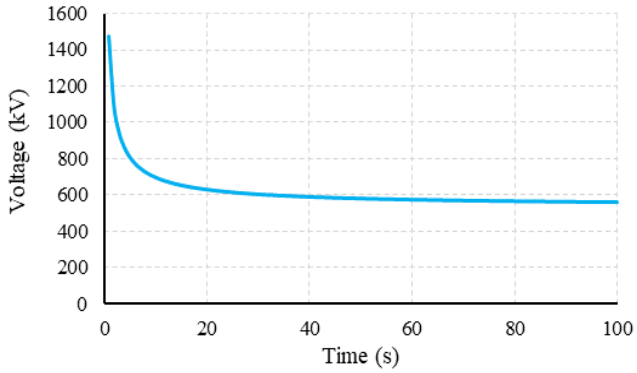
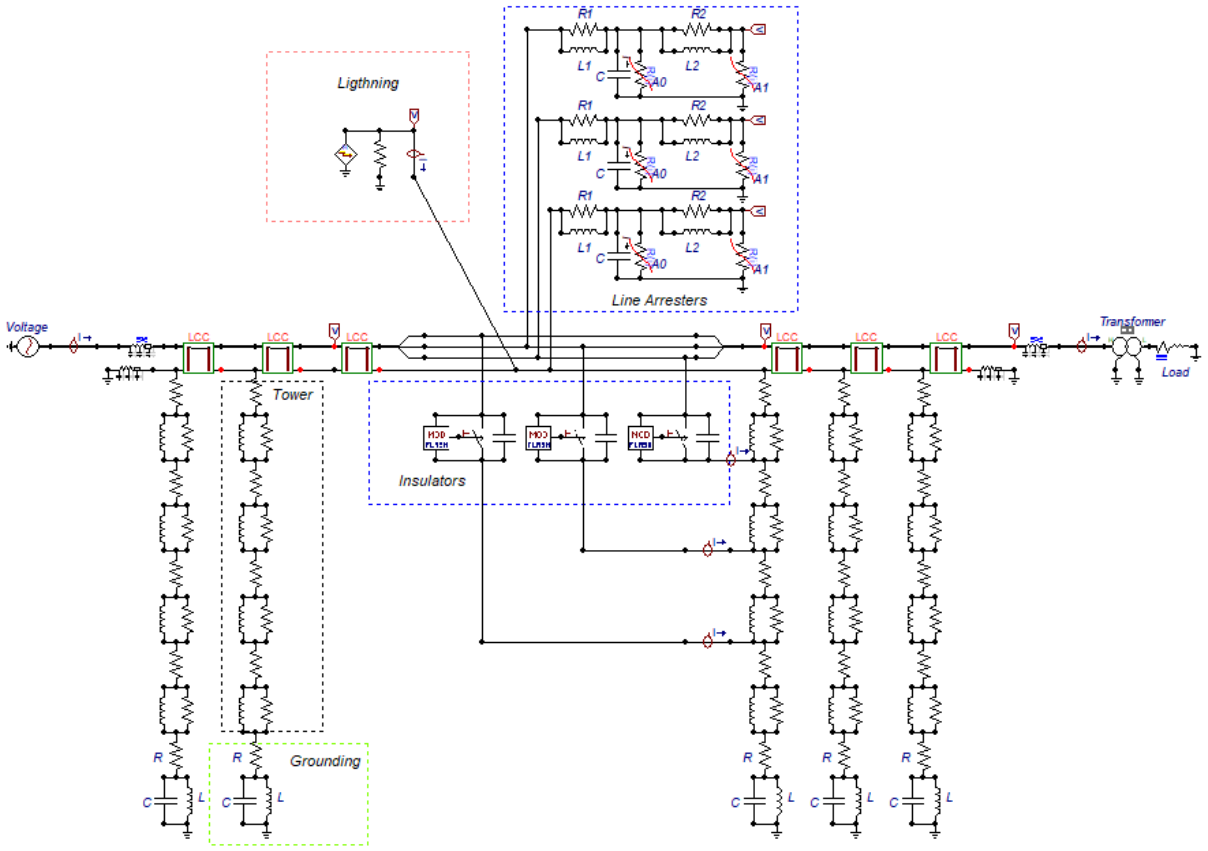


Figure 7. Flashover insulator voltage

5. Result and Discussion

Figure 8 simulates a 150kV single-circuit transmission system using ATP-EMTP software. The transmission line is connected to an AC generator at one end representing the generation source,. The other is connected to a transformer and load, illustrating the substation through the transmission line impedance matrix. The system is rated at 150kV to indicate that the line is powered by steady-state AC voltage. Lightning models, isolators, arresters, and grounding are connected to the system to analyze arrester performance according to parameter variations.



Effect of Lightning Current Amplitude

From Figure 9 it can be seen that the overvoltage that occurs in phase A increases the amplitude with the increase in the peak current of the impulse current. The overvoltage could be 2 MV for 40kA peak impulse current due to the absence of an arrester. The relationship between the increase in lightning current and overvoltage in phase A for various lightning current amplitudes is shown in Figure 9. This overvoltage exceeds the overvoltage of the insulator, so it can cause flashovers, that can continue to be back flashovers.

When a surge arrester is connected, the overvoltage becomes much lower than the insulator's overvoltage withstand, resulted in no flashover occurring for all peak impulse current amplitudes as shown in Figure 10. To protect power system equipment against damage due to lightning overvoltage, which can reach 2 MV, seamless surge arrester is connected in parallel with the insulator. This method can protect the power system equipment from damage.

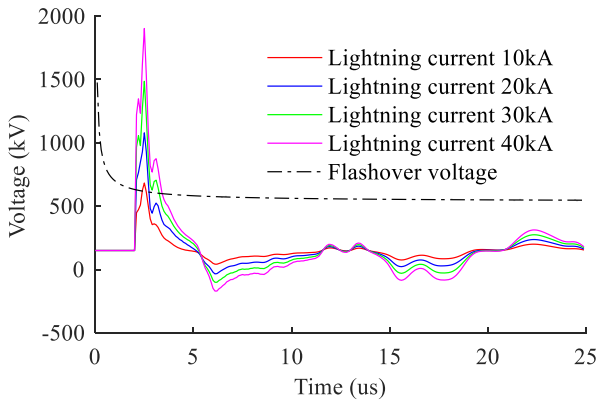


Figure 9. Effect of lightning current magnitude on overvoltage at phase A before using arrester

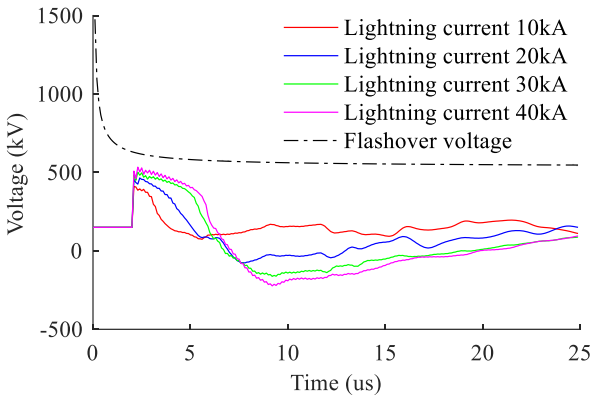


Figure 10. Effect of lightning current magnitude on overvoltage at phase A after using arrester

Figure11 shows a comparison of peak overvoltage in transmission lines with and without arresters for various lightning currents. Connecting surge arresters throughout the transmission system has a definite effect on protecting equipment from lightning overvoltage. It can be seen in Fig 11 that that the peak overvoltage without an an arrester can riserise until 2 MV for lightning current 40 kA. After applying a surge arrester, the peak overvoltage decreases to an average of about 500kV for all lightning currents.

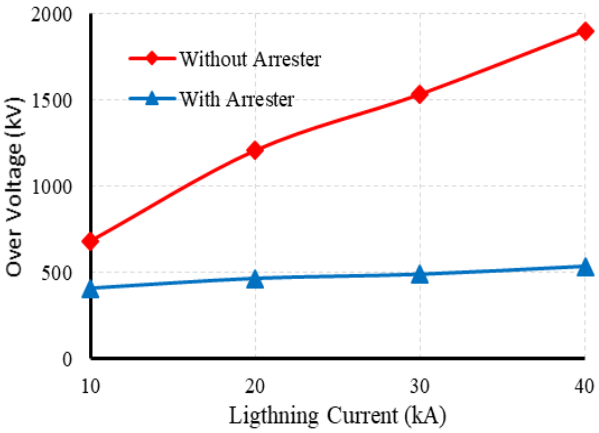


Figure 11. Comparison of peaks overvoltage at different lightning amplitude with and without arrester

Effect of Lightning Characteristics

Figure 12 shows the effect of lightning front time on the induced overvoltage in the transmission line without arresters. When one of the transmission line ground wires is struck by lightning, an induced overvoltage will flow across the phase wires. The highest induced voltage occurs when an impulse current with a short front time duration (1.2 us) strikes the ground wire. The overvoltage that passes through the insulator is about 2.7 MV, as shown in Figure 12.

The relationship between the induced overvoltage and the variation in lightning front time shows an inverse correlation between them. It can be seen in Figure12 that that that that the more minor the lightning current front time, the greater the induced overvoltagethe induced overvoltage.

Figure 13 is the induced overvoltage for the variation of the lightning front time in a transmission line with an arrester. When the surge arrester is connected, the induced voltage of about 2.7 MV drops

suddenly until it reaches a value of about 500kV, which is well below the transmission isolation resistance voltage and lower than 50%.

Figure 14 illustrates the variation of the induced overvoltage versus lightning front time with and without a surge arrester. It is concluded that the shorter the lightning current front time or the narrower the lightning impulse current rise time, the greater the induced overvoltage and can increase the flashover voltage of the insulator.

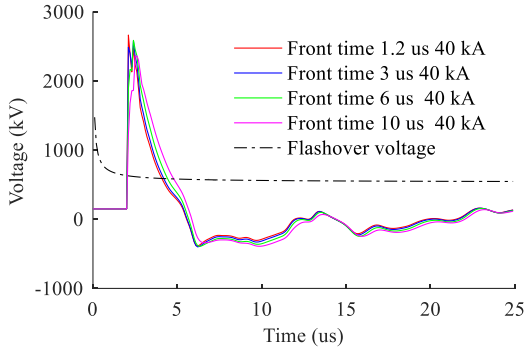


Figure 12. Effect of lightning front time on overvoltage at phase A before using Arrester

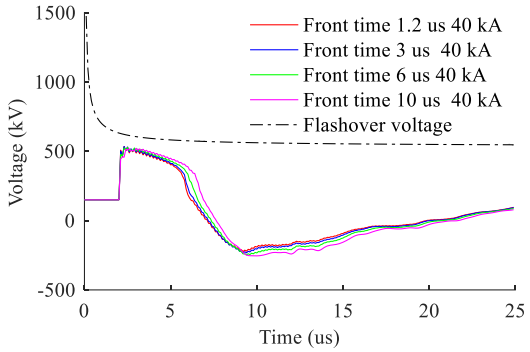


Figure 13. Effect of lightning front time on overvoltage at phase A after applying arrester

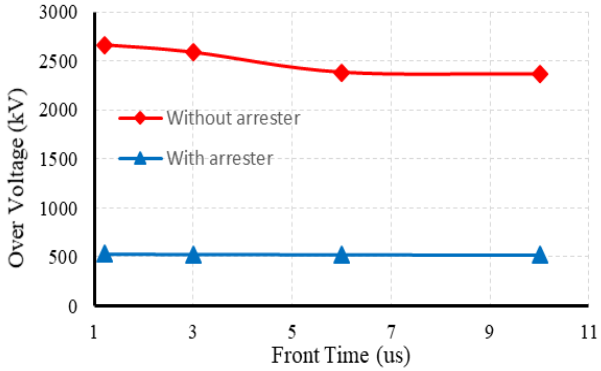


Figure 14. Comparison of peaks overvoltage at different front time with and without arrester

Figure 15 shows the effect of lightning tail time on the induced overvoltage in the transmission line without protection arresters. The highest induced overvoltage occurs when an impulse current with a long tail times duration is aboutabout us,, strikes the ground wire. The overvoltage that passes through the insulator is about 2.5 MV,, as shown in Figure 15. Generally, the

tail time lightning current is not significantlylinfluencednbyd by the induced overvoltage. Tail time from 20 us to 100100 produced about 2.3 to 2.5 MV for the the transmission line without arresters.

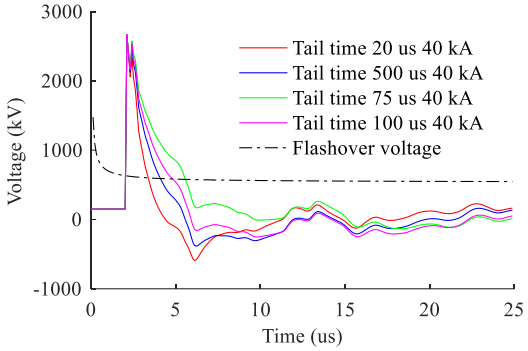


Figure 15. Effect of lightning front time on overvoltage at phase A before using Arrester

When the surge arrester is connected, the induced voltage dropsdrops about 550kV for all lightning tail time values,, as shown in Figure 16.

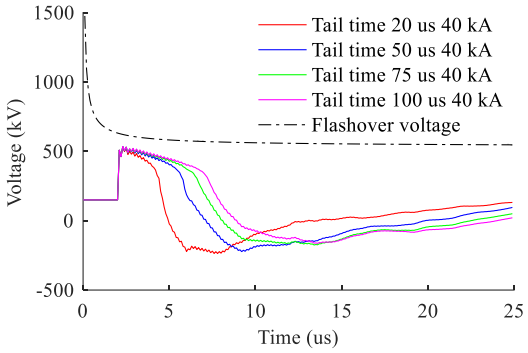


Figure 16. Effect of lightning tail time on overvoltage at phase A after using Arrester

Figure 17 shows the peak of induced overvoltage for the variation of the lightning tail time in a transmission line with and without applied arresters. It can be seen that the tail time of lightning curdoesnt dohave es not influenconovervoltage. The peak overvoltage without an an arrester waswas constant at 2.7 MV for all lighting current tail times. The peak overvoltage with the arrester is about 550kV for all lightning current tail times, as shown in Figure 17.

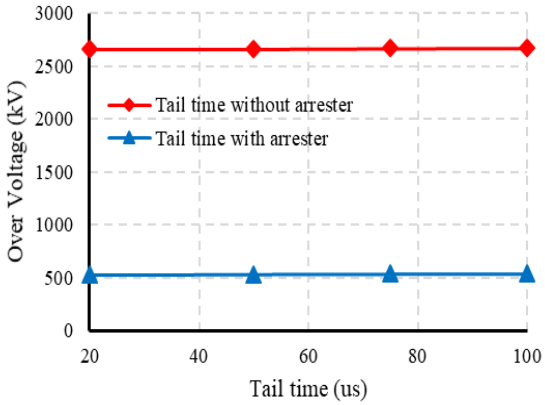


Figure 17. Comparison of peak overvoltage at different tail times with and without arrester

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Effect of Tower Grounding

In this simulation, tower grounding uses horizontal and vertical electrodes for protection against lightning overvoltage. The value of the grounding impedance of the tower footing during an impulse fault is characterized by many parameters such as: earth resistivity in Ohms m; electrode length in meters; soil permittivity in F/m; soil permeability in H/m; electrode implantation depth in meters; electrode radius in meters [19]. The magnitude of overvoltage of each type of grounding impedance without applied arresterarrester can be seen in Figure 18 and with arrester in Figure19 respectivelyrespectively.

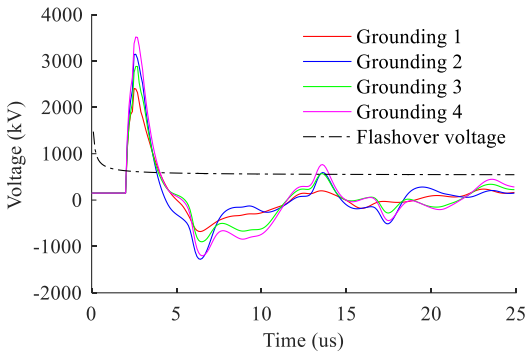


Figure 18. Voltage on phase-A at various types of grounding systems without arrester

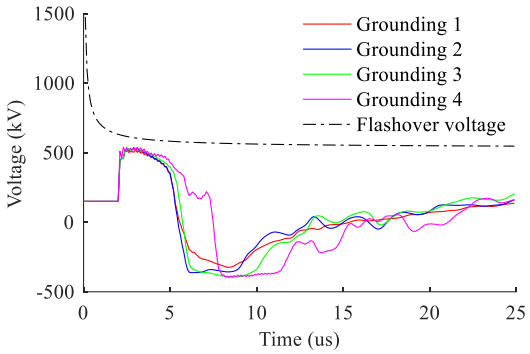


Figure 19. Voltage on phase-A at various type of grounding system with arrester

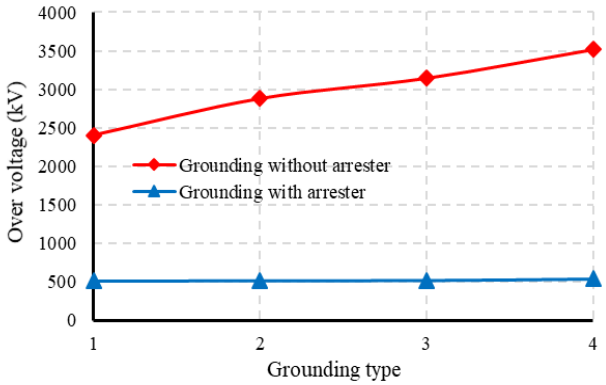


Figure 20. Peaks overvoltage at different grounding types before and after applying arrester with and without arrester

Figure 20 compares peak overvoltage for all types of grounding systems with and without arrester. The overvoltage increased with the increase in the resistance of grounding for the system without an arrester and tended to remain constant with a system with an applied arrester.

6. Conclusion

In this study, several parameters were analyzed that affect the induced overvoltage in the 150 kV transmission system before and after using a surge arrester. This study examines the effect of lightning current amplitude, front time and tail time of lightning impulses, and grounding impedance on the back flashover phenomenon before and after arrester installation. This study modeled and simulated all components of the transmission system, lightning impulses,, and grounding impedance using ATP-EMTP software. The simulation results show that the magnitude of the lightning current amplitude significantly affects the overvoltage. The higher the lightning current amplitude, the greater the overvoltage that occurs. Furthermore, the magnitude of the overvoltage is reduced by increasing the lightning current front time. At the same time, the effect of tail time is almost negligible on the magnitude of the induced voltage.

The effect of grounding impedance is not too significant in terms of the increase in overvoltage. The transmission system provides better performance when a lightning strike strikes the ground wire after installing a surge arrester compared to a transmission system without a surge arrester. The 150kV transmission line-induced voltage was reduced by more than 50% after using a surge arrester for all investigated parameters. This shows that to protect high voltage transmission circuits from lightning strikes and from failure or damage, arresters are used as overvoltage protection.

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