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# Impact of First Tower Earthing Resistance on Fast Front Back-Flashover in a 66 kV Transmission System

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**Abstract:** Lightning stroke on a transmission tower structure is one of the major reasons that results in high voltages at the tower arms due to the excessive lightning current flowing through the transmission tower to earth. The Surge voltage seen at the tower cross arm on the first tower close to a substation is the worst case. If this voltage is higher than the withstand level of the insulator string, the insulation of substation equipment will be exposed to transient over-voltage called fast front back-flashover (FFBF). The peak of this transient overvoltage is affected by the value of the system's earthing resistance. This paper studies the effect of reducing the grounding resistance of both the surge arrester (SA) and the first transmission line tower adjacent to a 66 kV substation on FFBF. Three case studies using PSCAD/EMTDC software are presented to simulate the variation of the potential siren at the substation equipment with different resistance values for the first tower and SA earthing resistance. The paper also addresses the economic protection system for solving the problem of transient overvoltage. The study proves that the proper design of the first tower grounding system enhances the safety of the system and reduces the cost for the grounding system to the minimum.

**Keywords:** back-flashover; insulation coordination; fast front transient study; footing resistance; lightning impulse withstand voltage; PSCAD/EMTDC

## 1. Introduction

Fast front back-flashover (FFBF) is an effective phenomenon across the insulator. It occurs when a fast front time lightning stroke hits an overhead transmission line (OHTL) sky wire or overhead tower. The high-current flowing through the tower surge impedance and footing resistance produces a transient overvoltage on this tower [1]. If the voltage across the tower insulator exceeds the insulator voltage withstand capability, a back-flashover will occur causing a significant overvoltage on the power line. If the resulting overvoltage at the equipment exceeds the basic insulation level (BIL) of installed equipment, insulation damage will likely happen [2].

The insulation strength of any equipment must be selected to avoid damage in case of overvoltages related to lightning strikes. The occurred overvoltage includes fast front overvoltage (FFO), switching actions (slow front overvoltage (SFO)), or the phenomena related to fundamental frequency overvoltages (temporary overvoltage (TOV)). A suitable surge arrester (SA) should be designed and located properly to avoid exceeding the basic insulation level (BIL) of equipment [3,4].

The effect of tower footing earthing resistance on the fast front back-flashover study has been conducted in some research [4,5]. The striking current and the tower footing resistance values required to make back-flashover on the tower insulators are determined in [4,5]. According to these references, if the magnitude of lightning stroke is more than 50 kA, the back-flashover on the tower insulators will occur whatever the value of the tower footing resistance.

The propagation of lightning surge is analyzed with the variation of tower footing resistance in [6]. The value of footing resistance was varying between 4–35  $\Omega$ , while the proper design for the tower footing resistance was found to be maintained between 5–6  $\Omega$  to avoid the electrical stresses on both the power line insulation and surrounding structures [6]. Preventing the back-flashover on tower insulators by controlling the towers' footing resistance is studied in [4–6].

When a lightning strike hits the transmission tower or ground protection wire, a conducted surge voltage on the tower structure will be produced. Another surge voltage with the same wave shape and less magnitude will be induced on the power phases [7,8]. The voltage magnitude across to the insulators is the same as the difference between the two surge voltages. The back flashover is expected to occur on the phase which has the highest instantaneous power-frequency voltage value of opposite polarity [3].

Reference [9] stated that when a lightning stroke current hits an object, the induced voltage is inversely proportional to the distance from the hit object. It also stated that the magnitude of induced voltage decreases while increasing striking distance. The maximum induced voltage is at the point nearest to the strike point location.

Reference [10] studied the high efficient lightning protection system using underbuilt wires. The underbuilt wire has effective protection, easy for installation, and low cost. Nevertheless, it decreases the phases to ground clearance. So, the underbuilt wires are not appropriate for the old transmission lines with weak towers and for the road crossing lines, or crossing buildings, rivers, etc., where high clearances to the ground are required.

Using counterpoise wires for the towers' grounding system will improve in the earthing system power frequency resistance value and the related impulse grounding resistance will be improved. The transient overvoltage will be decreased accordingly. In [11], the influences of the length of counterpoise earth wire are studied and the effective length formula for the counterpoise wire is proposed. The effective length of the counterpoise wire is in direct proportion to the soil resistivity values and front time of applied impulse current, while it varies inversely with the lightning current magnitude [11].

Reference [12] illustrates the guidelines for lightning surge analysis using the electromagnetic transient program (EMTP) recommended in Japan where a comparison study between lightning surge analysis using EMTP and the numerical electromagnetic analysis method is made in [13].

Reference [14] describes the factors affecting the back-flashover across insulator in a transmission system. This study focused on the magnitude of lightning stroke current and front/tail times of lightning stroke impulse.

SA grounding resistance is important to protect the equipment against back-flashover, so a good grounding system for SA's earthing point will considerably reduce the corresponding insulation breakdowns. IEEE Std.80 [15] and IEEEStd.142 [16] standards recommend that surge arresters earthing resistance should be as low as possible and shall be connected by a direct path to the main grounding system. Also, UK earthing design standard EA TS 41-24 [17] and reference [18] stated that the surge arrester effectivity may be impaired unless connected to the low grounding resistance value. However, very low grounding resistance values may cause increasing the probabilities for surge arresters' damage due to the high discharged currents flowing through them and energy absorption capability [19].

The ground protection wires installed in the transmission lines are not sufficient to protect the electrical network against lightning strikes. So, the towers footing resistances should be improved. Otherwise, the substation connected to these transmission lines is not safe against lightning stroke in the adjacent towers [8].

Some techniques are introduced to control the back-flashover by reducing the grounding system of the towers located close to the substation [8,20]. These studies investigated the impact of keeping the foot impedances of the first three towers or the first five to seven towers close to a minimum; however, no analysis, case studies, or recommendation criteria are presented in these references. Also, studying the impact of the first tower only has not been studied in these references.

Reference [21] studied the effect of installing lightning protection devices attached to tower insulators (insulator with a built-in surge arrester) on reducing fast front overvoltage on distribution lines.

Reference [22] studied the performance of back-flashover with the installation of the multi-chamber insulator arresters (MCIA) using software simulation to compare between transmission line model with and without MCIA. It is recommended to replace all the conventional insulators strings with MCIA strings to protect the system from the back-flashover effect. Nevertheless, replacing all the conventional insulators with new MCIA insulators becomes a strenuous effort and a very costly solution.

Reference [23] studied the effect of changing tower footing resistance on FFO during FFBF in the medium voltage (MV) traction system.

Preventing back-flashover on tower insulators is investigated in [5,14] via determining the magnitude and shape of the lightning current that leads to back-flashover on the tower insulators. Moreover, some efforts were discussed in [9–11] to prevent the back-flashover on tower insulators by using counterpoise wires to improve the towers' footing resistance. Nevertheless, these researchers did not study the transferred back-flashover on the phase conductors. They also did not analyze the effect of the FFO on the substation components and they did not investigate the behavior of installed SA for overvoltage protection during the FFO.

The work proposed in [15–19] mentioned the importance of the SA earthing resistance to reduce the insulation breakdown. However, the detailed influence of SA earthing resistance on the FFO has not been studied. Furthermore, no analysis, case studies, results, or recommendation criteria for the SA earthing resistance are provided.

References [24–27] studied the behavior of power frequency earthing resistance and soil resistivity during fast front overvoltages. The different forms for impulse resistance with the lightning strike current are illustrated. Nevertheless, the impact of reducing footing resistance is not investigated in these studies.

The work proposed in [8,20,23] mentioned the importance of the interconnection between the earthing system of transmission lines and substation earthing mat. However, the detailed influence of the interconnection on the FFO has not been studied. Furthermore, no analysis, case studies, results, or advantages or disadvantages for the interconnection are provided.

The main contributions of the proposed approach in this paper can be summarized as follows:

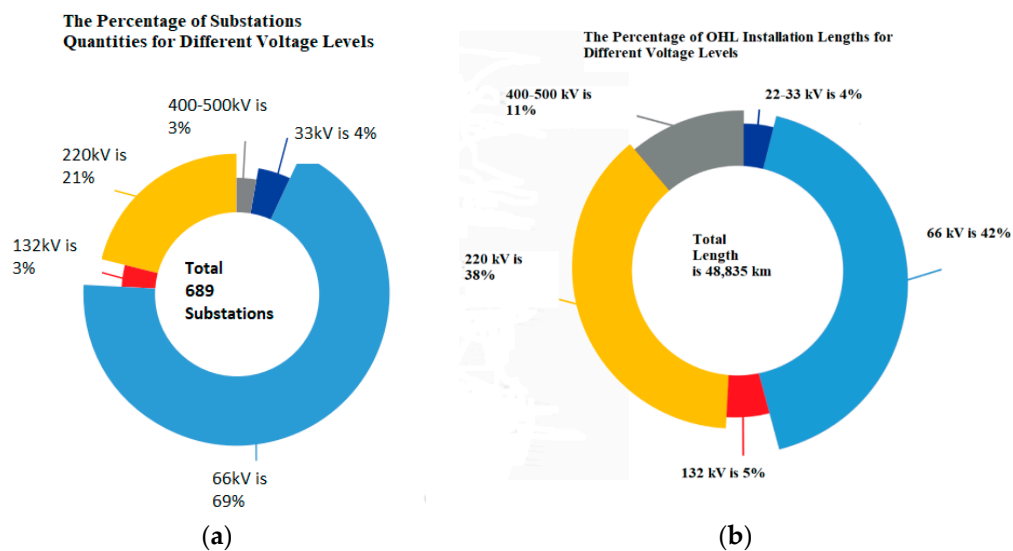
1. Solving the insulation damage problem for the substation elements due to back-flashover by improving the footing resistance of only the first adjacent tower to the substation. This is considered the most techno-economic solution to prevent substation equipment insulation damage due to FFBF.
2. Economic evaluation and substantive costing studies are provided for the proposed technique. Hence, the study validated the proper design of the first tower grounding system, enhances the safety of the system, and reduces the cost for the grounding system to the minimum.
3. The impact of the second, third, and fourth towers footing resistance on the FFO on the power line during back-flashover is analyzed. Furthermore, the percentage of maximum overvoltage decreasing (PMOD) for each tower due to FFBF is proposed.
4. The detailed influence of SA earthing resistance on the FFO to prevent the damage of equipment insulation is studied. Moreover, the recommended criteria for the SA earthing resistance are provided.
5. The advantages and disadvantages of interconnection between the transmission line grounding system and substation grounding system on the calculation of fast front overvoltage (FFO) and ground potential rise (GPR) are proposed in this paper.

The study in this paper starts in Section 2, where the guidelines for complete modeling of a 66 kV substation are presented. The modeling of the back-flashover is described in Section 3. Three case studies and the simulations results are illustrated in Section 4 and the conclusions are presented in Section 5.

## 2. Power System Modeling

The proposed study was applied to a 66 kV transmission line for the following reasons:

- This voltage level is the most commonly used in Egypt Electricity Transmission Company (EETC) connected to medium voltage substations [28] as shown in Figure 1.
- Due to its low nominal voltage, the corresponding basic insulation level (BIL) for its components is also relatively low, and hence, the study of overvoltage due to lightning extremely becomes important.
- FFO is very critical when the system voltage is below 245 kV [29].
- The lower the system voltage, the higher the probability of a back-flashover occurs as shown in Figure 1 [4].



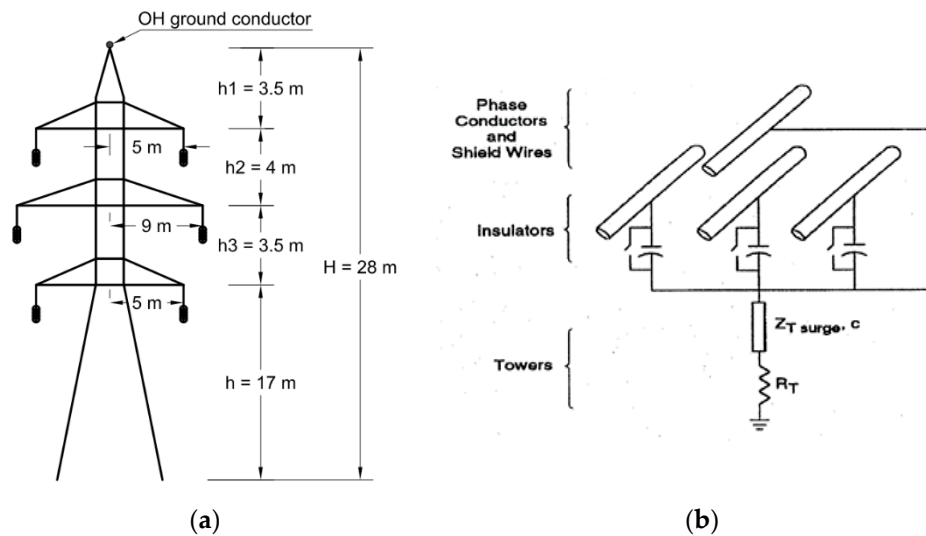
**Figure 1.** Substations and transmission lines (TLs) with different voltage levels in Egypt. (a) The percentage of substations quantities for different voltage levels; (b) the percentage of overhead line (OHL) installation lengths for different voltage levels [28].

The corresponding insulation withstand voltage (BIL) for 66 kV is low relative to the other high voltage levels 500, 400, 220, and 132 kV. As shown in Figure 1, the 66 kV system has the greatest percentage of substations quantities and transmission line lengths as well. The flashover incidence is a function of the installed length of OHL and the withstand voltage of the insulation system [30], so the expected number of insulation flashovers in the 66 kV transmission line is very high; consequently, solving the problem of FFBF in the 66 kV network is very important.

The accuracy of the fast front overvoltages (FFO) calculation largely depends on the accuracy of the modeling method of each component in the power system. During fast front back-flashover and due to the high current and frequency values, the power system components must be modeled with their capacitances to ground, surge impedance, and velocity of propagation values [31]. This section encompasses the modeling of each power system component during the FFO.

### 2.1. Modeling of Tower

The wave shapes of lightning surges are affected by tower modeling. Figure 2a shows the tower configuration whereas Figure 2b shows the model of the used tower and transmission line [32]. The tower is modeled by its configuration entered into the PSCAD program. The software calculates the tower parameters considering both self-inductance and resistance as per reference [33]. The surge impedance of the tower depends on the structure details, and it is calculated according to the procedure outlined in [33]. Formulas to calculate this parameter are given in [30,33,34]. Typical values range from 100 to 200  $\Omega$  [7]. The velocity of propagation can be assumed to be equal to the speed of light [32]. In this paper, the surge impedance of the tower is assumed to be 150  $\Omega$ .



**Figure 2.** (a) A 66 kV transmission tower configuration; (b) modeling method for overhead transmission line and tower with its insulators in PSCAD [23,35].

### 2.2. Modeling of Transmission Line

For the 66 kV transmission line, the overhead ground wire and spans were modeled using the frequency-dependent model in PSCAD [9]. The frequency-dependent phase model was used.

### 2.3. Modeling of Tower Footing Resistance

The grounding resistance for the tower footing varies with the fast front surge's current magnitude. This is due to soil ionization and soil breakdown characteristics. When the surge current increased, the corresponding voltage gradient exceeds a critical value. This leads to a conductive pathway for current flow and causing soil breakdown. Hence, the tower footing resistance during fast front current is less than the measured resistance at the power frequency during the low current. The tower footing resistance during fast front current is represented by the following formula, Equation (1) in [2,30,32].

$$R_i = \frac{R_0}{\sqrt{1 + \left(\frac{I_R}{I_g}\right)^2}} \quad (1)$$

where:

$R_0$  the measured tower footing resistance at low current and low frequency ( $\Omega$ ).

$R_i$  tower footing impulse resistance ( $\Omega$ ).

$I_g$  limiting current to initiate sufficient soil ionization (kA).

$I_R$  lightning current through the footing resistance (kA).

The limiting current is a function of soil ionization and is given by Equation (2) [30]:

$$I_g = \frac{1}{2\pi} \frac{E_0 \rho}{R_0^2} \quad (2)$$

where:

$\rho$  soil resistivity ( $\Omega\text{m}$ ) and can be considered about 800  $\Omega\text{m}$ .

$E_0$  soil ionization gradient and can be considered about 400 kV/m.

As per IEEE 80 [14], the sandy loam soil resistivity is 800  $\Omega\text{m}$ , and the average soil resistivity for dry soil is 1000  $\Omega\text{m}$ . Most of the new projects in Egypt are located in the east and west Egyptian desert, where the soil is sandy. So, 800  $\Omega\text{m}$  value is assumed.

The towers' footing resistance is modeled by impulse resistance instead of the measured low-frequency footing resistance.

#### 2.4. Modeling of Line Insulators

The tower insulators are modeled as capacitors. The insulator capacitance is around 10 pF. So, each line insulator is represented in the PSCAD model with a 10 pF capacitor [2,32].

#### 2.5. Modeling of Surge Arrester

The surge arrester is designed to limit transient overvoltages and divert current waves to earth through its nonlinear resistance and limit the amplitude of this overvoltage to a value less than BIL of the substation protected equipment.

The SAs can be represented by two methods: simplified IEEE prepared by Pinceti Model and IEEE frequency-dependent model as shown in Figure 3a,b, respectively [36]. The frequency-dependent model for the SAs in the system was used in this study. As shown in Figure 3b, the two nonlinear resistors  $A_0$  and  $A_1$  are separated by an RL (resistor and inductor) filter. This filter is represented by inductance  $L_1$  and resistance  $R_1$  [37]. The impedance of the RL filter during a fast front surge is higher than its impedance during the slow front surge. So, more current flows in the nonlinear resistor  $A_0$  than in  $A_1$  during lightning strikes [2,36]. The inductance of the magnetic fields in the vicinity of the arrester is presented by  $L_0$ . The resistance  $R_0$  is used as the stabilizing of the numerical integration for the computer program, while capacitor C is the terminal-to-terminal capacitance of the arrester. The most important characteristics of these models are that their parameters are calculated from electrical data. The details of surge arrester frequency-dependent model parameters are presented in Equation (3):

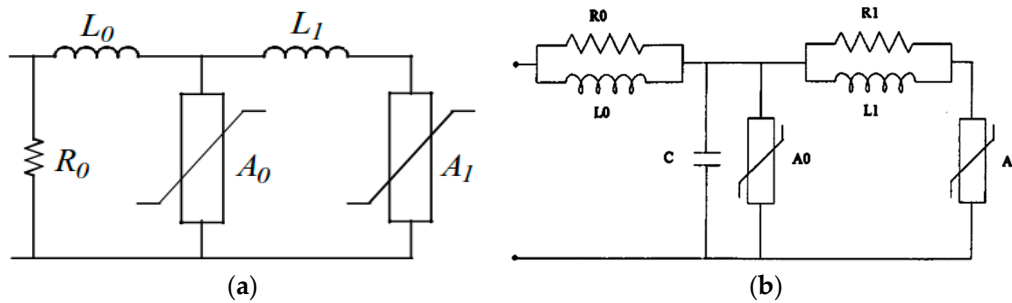
$$\begin{aligned} L_1 &= 15 \text{ d/n } (\mu\text{H}) \\ R_1 &= 65 \text{ d/n } (\Omega) \\ L_0 &= 0.2 \text{ d/n } (\mu\text{H}) \\ R_0 &= 100 \text{ d/n } (\Omega) \\ C &= 100 \text{ n/d } (\text{pF}) \end{aligned} \quad (3)$$

where:

d is the estimated height of the arrester in m (assumed to be 0.5 m).

n is the number of parallel columns of metal oxide in the arrester (assumed to be 1).

The nonlinear resistors  $A_0$  and  $A_1$  can be modeled as point by point V-I curve. Data for the V-I curve shall be taken from arresters' datasheets. The V-I characteristics of  $A_0$  and  $A_1$  are chosen to be the same as mentioned in [38].



**Figure 3.** (a) Surge arrester SA simplified IEEE model prepared by Pinceti; (b) SA IEEE frequency-dependent model.

### 2.6. Modeling of Voltage and Current Transformers

The voltage and current transformers were simulated by their stray capacitance to the ground, which was 500 and 250 pF, respectively [2,32,35].

### 2.7. Modeling of Disconnecting Switch

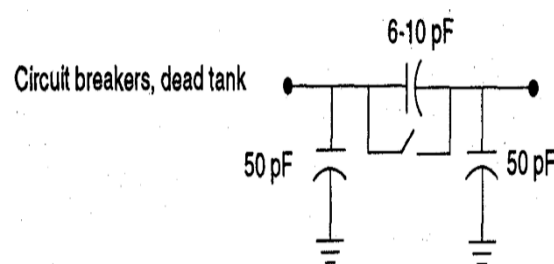
The disconnecting switch was simulated by its stray capacitance to the ground. The capacitance-to-ground was 100 pF [2,32,35].

### 2.8. Modeling of Bus-Bar Support Insulator

The bus-bar support insulator was simulated by its stray capacitances to ground. The capacitance-to-ground was 80 pF [2,32,35].

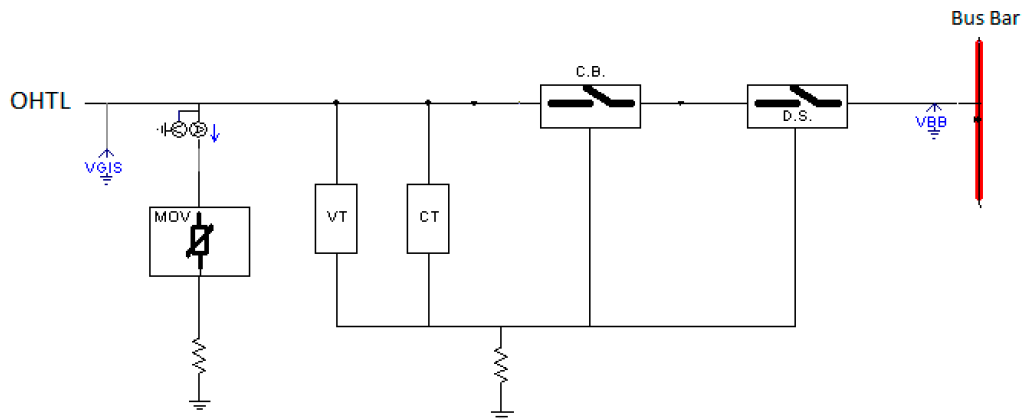
### 2.9. Modeling of Circuit Breaker

The circuit breaker during fast front lightning surge study was simulated by its stray capacitance to ground. The capacitance-to-ground value range was 50–100 pF [2,32,35]. The dead tanks circuit breakers are represented with its capacitance values as shown in Figure 4. If the circuit breakers have more support, the appropriate insulation capacitances for this support should be added to the model [32]. A 600  $\mu\Omega$  circuit breaker contact resistance was also added during the circuit breaker pole closing position.



**Figure 4.** Dead tank circuit breaker stray capacitance simulation during fast front [23].

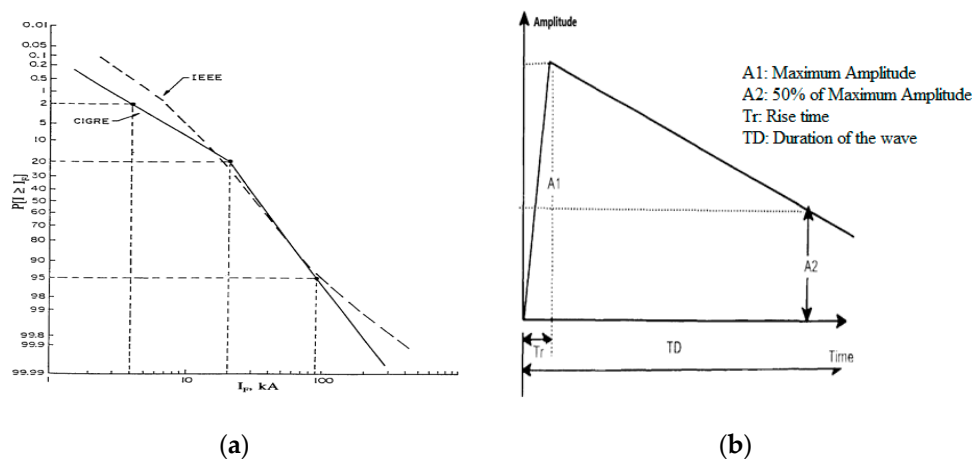
Figure 5 shows one switchgear bay, which includes the bus-bar, disconnecting switch, circuit breaker, current transformer, voltage transformer, and SA as simulated in the PSCAD/EMTCD [39] model.



**Figure 5.** PSCAD/EMTDC simulation of switchgear components bonded to the substation grounding system.

### 3. Modeling Back-Flashover

The probability distribution of negative lightning current amplitude recommended by international council on large electric systems CIGRE for lightning statistical studies is shown in Figure 6a [30]; the probability of back-flashover depends on this graph. The formulae used for the calculations are based on Eriksson Weck—simplified procedures for determining representative substation impinging lightning overvoltages [40].



**Figure 6.** (a) CIGRE and IEEE stroke current probability curves, first stroke negative downward flash [7,23]; (b) simplified current source of the lightning surge [23,35].

Lightning stroke current waveforms by cloud-to-ground discharges can have a simplified description in terms of parameters such as peak current, rate of rise, rise time, and tail time. Figure 6b shows the simplified current source representation of the lightning surge used in this paper [35]. Lightning stroke hits the ground wires. The lightning current discharges to the ground through the tower surge impedance and tower footing resistance yielding an overvoltage on the tower insulators. When the voltage across the insulator exceeds the insulator voltage withstand capability, back flashover occurs (simulated by closing the parallel switch) on the insulator string [1].

The peak impulse current strike on ground wires is normally 80–200 kA. A value of 200 kA is chosen in this paper according to [2,4,5]. Since the probability of occurrence for 200 kA peak is less than 1%, the lightning impulse is modeled as a current source with a simplified wave shape as shown in Figure 6b. It has 4.5  $\mu$ s front time and 75  $\mu$ s tail time as per the worst case stroke event as mentioned in Table 1 [2]. When the magnitude of lightning stroke is more than 50 kA, the back-flashover on the tower insulators is always occurring with any tower footing resistance [4].



**Table 1.** CIGRE concave wave shape parameters for stroke currents used in this study.

Parameter	Stroke (Worst-Case Stroke Event)
Peak current	200 kA (Less than 1% probability the stroke exceeding this peak current)
Maximum front steepness	60 kA/ $\mu$ s
Equivalent front time	4.5 $\mu$ s
Time to half	75 $\mu$ s

The flashover occurs when  $V_t - V_{sys} > \text{gap flashover voltage } (V_{FO})$ .

$$V_t = F(I_x, Z_t, Z_g) \quad (4)$$

where:

$V_t$  Tower surge voltage.

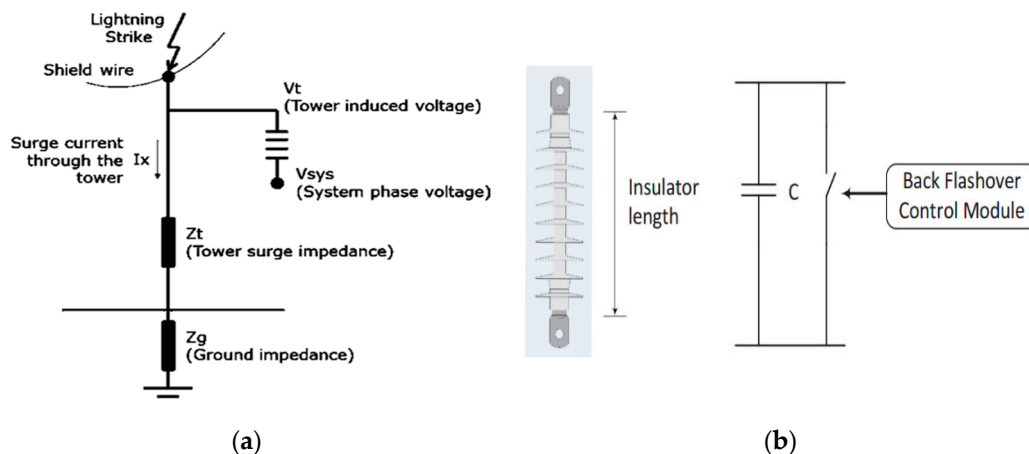
$V_{sys}$  System voltage.

$I_x$  Lightning strikes current.

$Z_t$  Tower surge impedance.

$Z_g$  Footing grounding impedance.

Back-flashover occurs when the strike current travels to earth through tower surge impedance and tower footing grounding impedance as shown in Figure 7a. The Back-flashover event is represented by a bypass switch (Control Module) in parallel with the insulator capacitance as shown in Figure 7b [2].



**Figure 7.** The equivalent circuit of the tower during a lightning stroke: (a) back-flashover propagating and tower simulation during fast front back-flashover (FFBF) [1,23]; (b) tower insulators back-flashover model in PSCAD [2,23].

### Modeling Insulator Strings in Lightning Studies

Several models have been proposed to represent insulator strings in lightning studies. One of these models relies on the application of the leader progression model when a leader propagating from one electrode reaches the other, or when leaders propagating from both electrodes meet in the middle of the air gap [1], whereas the other models are based on voltage-time curves reference [41]. In this paper, the transmission line insulator string flashover has been modeled by volt–time characteristics. Flashover occurs when the potential difference across the insulator strings becomes equal to or higher than the flashover strength. The  $V_{FO}$  (kV) is calculated by the following equation [2,22,42].

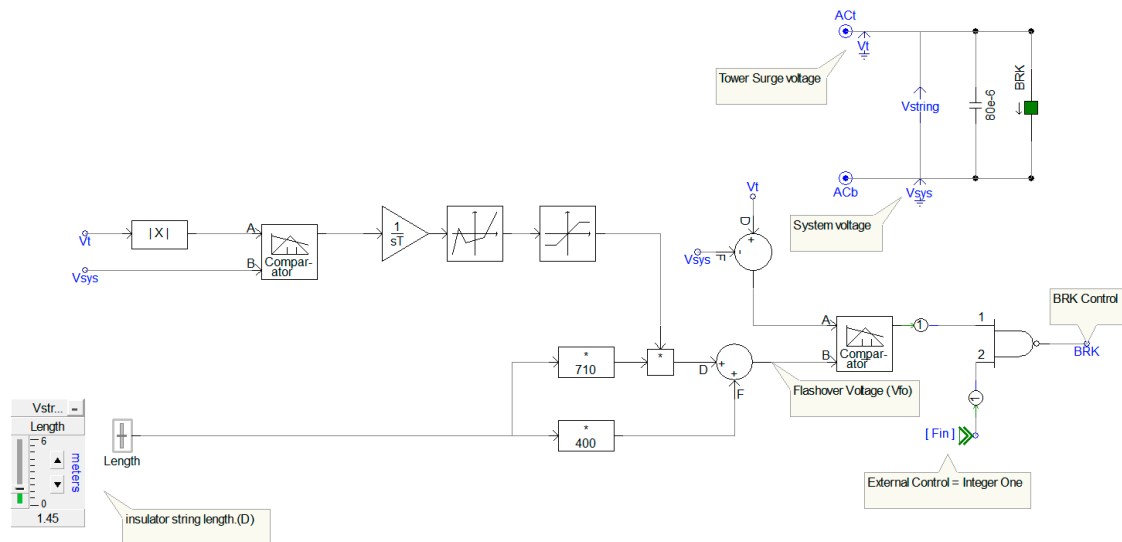
$$V_{FO} = (400 + 710/t_c^{0.75})D \quad (5)$$

where:

$D$  (m) The insulator string length.

$t_c$  ( $\mu$ s) The time to flashover.

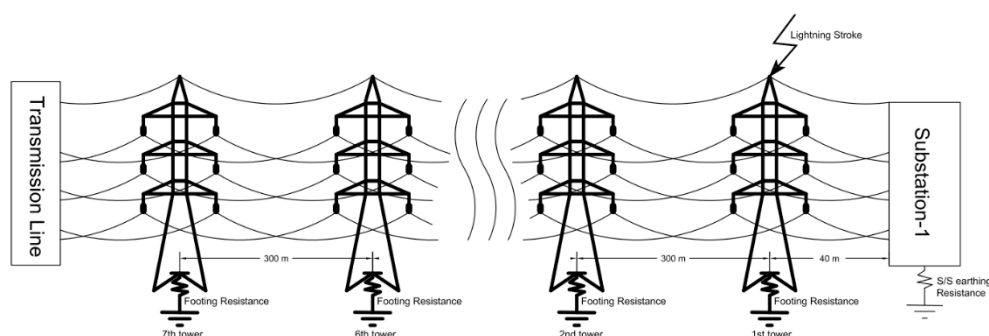
The back-flashover is modeled by a parallel switch with the insulator capacitance. The closing of the switch is controlled by an external control module. This control module compares the voltage applied to the insulator with the insulator volt–time characteristics (flashover voltage). When the voltage across the insulator exceeds the flashover voltage ( $V_{FO}$ ), the external control module issues signal to close the parallel switch [2,22,42]. Figure 8 shows the wave-dependent back-flashover control module for the transmission line insulator.



**Figure 8.** Wave-dependent back-flashover control module for transmission line insulator.

#### 4. Simulation Studies

We simulated 7 km transmission lines (TL) connecting two 66 kV substations as shown in Figure 9. Since the impact of the surge vanishes after 4 to 7 towers [4,5,9], only seven towers were included in the simulation.



**Figure 9.** The system schematic diagram illustrates the overhead (O.H.) towers, spans, strike location, and substation (S/S) connection.

The first TL tower is located 40 m away from the substation and the span length between every two towers is assumed to be 300 m [9]. The lightning surge, for the worst case, was assumed to hit the first tower as shown in the 3D schematic shown in Figure 10.

The substation single line diagram is shown in Figure 11. All substation equipment, transmission line, lightning strike, towers, and tower footing resistance have been simulated in PSCAD/EMTDC [39] as described in Sections 2 and 3.

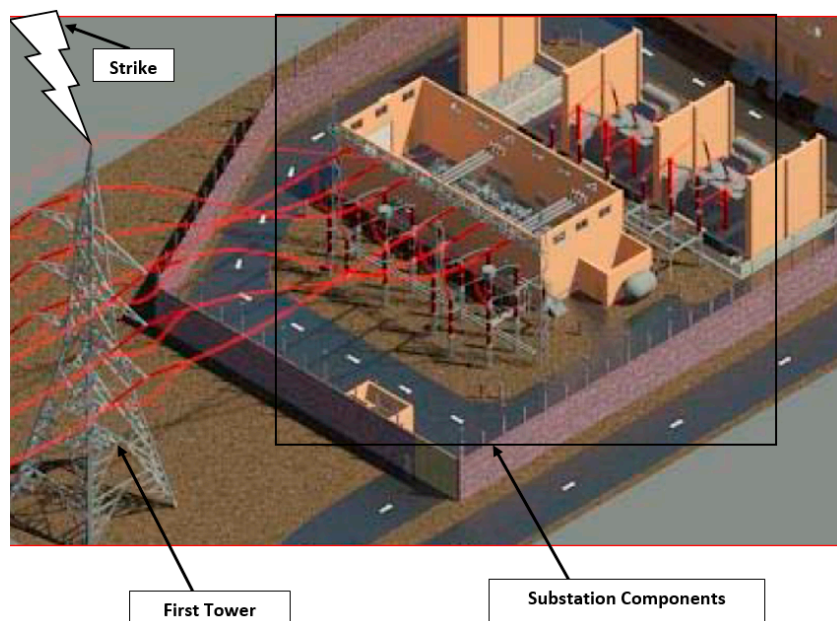


Figure 10. 3D substation layout illustrates the high voltage components.

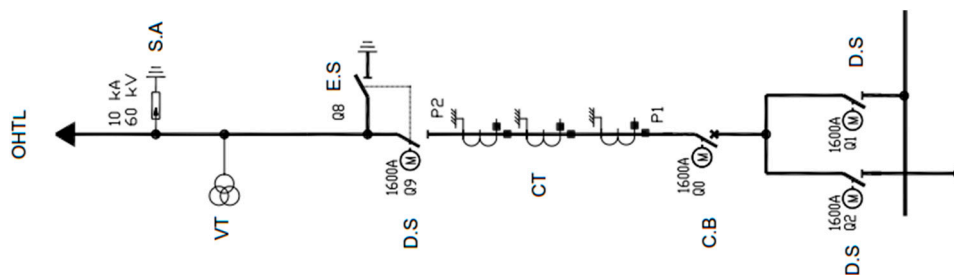


Figure 11. Single line diagram for 66 kV feeder bay.

In the following subsections, the substation FFO was examined under the following assumptions:

1. The maximum peak impulse current for the strike during back-flashover is 200 kA as a worst-case [4,5].
2. The rating of the lightning impulse withstands voltage (LIWV) of the substation equipment is taken as 325 kV [20].
3. The strike hits the first tower which is located 40 m away from the substation.
4. The value of towers' footing resistance varies between 5–100  $\Omega$  as per [6,15].
5. SA is located at the substation yard as shown in Figures 5 and 11 and is connected in parallel to the substation component at the coupling point between the transmission line and the substation entrance.
6. The substation grounding resistance is designed according to IEEE 80-2013 where the ohmic value of the ground substation is suggested to vary between (1  $\Omega$  to 5  $\Omega$ ) [15]. The SA is directly connected to the substation grounding system and grounded via the main grounding grid of the substation, consequently, the SA earthing resistance varies with the same values of substation resistance accordingly.

The transient overvoltage is calculated during the back-flashover using PSCAD/EMTDC [39] program at the substation terminal. The following case studies show the effect of enhancement of the first tower footing resistance and SA earthing resistance on the FFO due to back-flashover to an acceptable limit.

#### 4.1. Case A: Influence of Reducing First-Tower Footing Resistance

The towers' footing resistance for the base case in this study was taken as 100  $\Omega$  for all the towers as given in Table 2.

**Table 2.** Substation fast front overvoltages (FFO) and the towers footing resistance is 100  $\Omega$  for ALL towers (reference case).

Twr4_FR	Twr3_FR	Twr2_FR	Twr1_FR	Vt at S/S (kV)
100 $\Omega$	100 $\Omega$	100 $\Omega$	100 $\Omega$	463.28

In Table 2, the following definitions are used:

- **Twr1\_FR:** Value of the footing resistance in ( $\Omega$ ) of the first tower (Twr1) adjacent to the substation.
- **Vt at S/S (kV):** The calculated transient overvoltages at substation terminal during the back-flashover.

Starting from Table 3, the first tower footing resistance is changed gradually (tower by tower). In Table 3, the footing resistance in the first row is reduced to 25  $\Omega$ . Then the effect of reducing footing resistance for the other towers is examined in the next rows.

**Table 3.** Impact of reducing towers footing resistance 25  $\Omega$  on FFO.

Twr4_FR	Twr3_FR	Twr2_FR	Twr1_FR	Vt at S/S (kV)	PMOD (%)
100 $\Omega$	100 $\Omega$	100 $\Omega$	25 $\Omega$	427.9	7.6%
100 $\Omega$	100 $\Omega$	25 $\Omega$	25 $\Omega$	415.2	3.0%
100 $\Omega$	25 $\Omega$	25 $\Omega$	25 $\Omega$	413.9	0.3%
25 $\Omega$	25 $\Omega$	25 $\Omega$	25 $\Omega$	413.9	0.0%

Color highlighted cells are referring to towers' enhanced footing resistance.

The percentage PMOD (%) for the decreasing transient overvoltage at the substation terminal with the decreasing of the footing resistance is calculated as the following:

$$\text{PMOD (\%)} = \frac{V_{\text{Before_Enhancement}} - V_{\text{After_Enhancement}}}{V_{\text{Before_Enhancement}}} \times 100 \quad (6)$$

PMOD (%) is the percentage of maximum overvoltage decreasing due to FFBF. The PMOD (%) for the first row in all tables is calculated compared to the base case given in Table 2. The PMOD (%) for the other rows is calculated in comparison to the value in the previous row of the same table.

The footing resistance for the towers is examined with 100, 25, 15, 10, and 5  $\Omega$ , which are the typical values used in previous research [6,15,43].

The results given in the next tables confirm that the impact of reducing other towers' resistance is minimal. Reducing the earthing resistance of the second tower, for example, to 25  $\Omega$  will improve the reduction in FFO by only 3%. Reducing the resistance of the third tower is almost neglected.

Similarly, for Tables 4–6, the impact of reducing the first towers earthing resistance is high while the impact of the second towers earthing resistance is very low and the reduction due to the third towers is almost neglected. The results prove that any reduction in the far towers is economically unjustified.

As stated before, the rating of the lightning impulse withstands voltage (LIWV) of the substation equipment is 325 kV [20]. The value of calculated FFO is considered acceptable if there is enough margin between the voltage across the equipment (FFO) and the insulation's capability (325 kV). This margin should be over 20% (IEEE Std. C62.22-2009) [44]. So, the acceptable FFO in this study is 270 kV.

The study shows that any footing resistance above 5  $\Omega$  will cause the transient overvoltage to be greater than 325 kV and consequently will cause damage to the substation insulation. With 5  $\Omega$  footing resistance in the first tower only, the maximum transient overvoltage at substation components

is 303.7 kV as given in Table 6 and shown graphically in Figure 12. This value (303.7 kV) is less than LIWV (325 kV); however, this value still higher than the acceptable FFO (270 kV).

**Table 4.** Impact of reducing towers footing resistance 15  $\Omega$  on FFO.

Twr4_FR	Twr3_FR	Twr2_FR	Twr1_FR	Vt at S/S (kV)	PMOD (%)
100 $\Omega$	100 $\Omega$	100 $\Omega$	15 $\Omega$	399.8	13.7%
100 $\Omega$	100 $\Omega$	15 $\Omega$	15 $\Omega$	381.9	4.5%
100 $\Omega$	15 $\Omega$	15 $\Omega$	15 $\Omega$	380.5	0.4%
15 $\Omega$	15 $\Omega$	15 $\Omega$	15 $\Omega$	380.5	0.0%

Color highlighted cells are referring to towers' enhanced footing resistance.

**Table 5.** Impact of reducing towers footing resistance 10  $\Omega$  on FFO.

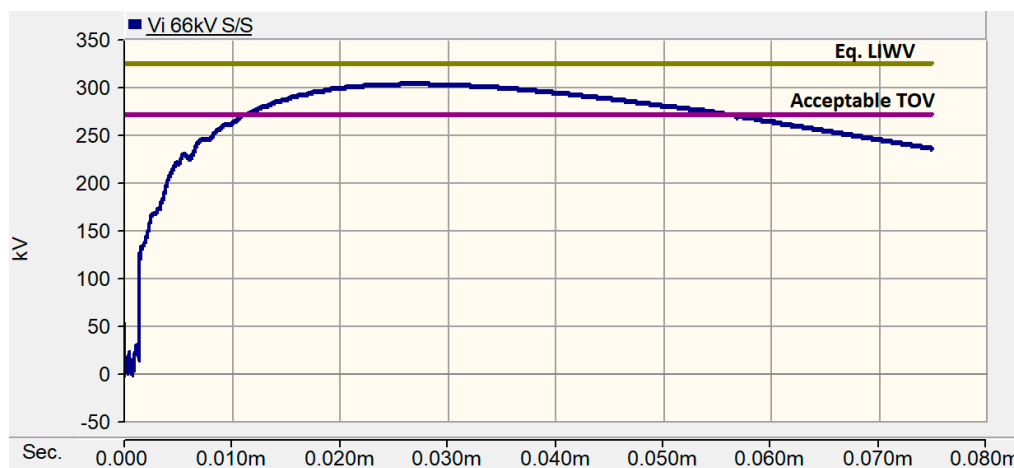
Twr4_FR	Twr3_FR	Twr2_FR	Twr1_FR	Vt at S/S (kV)	PMOD (%)
100 $\Omega$	100 $\Omega$	100 $\Omega$	10 $\Omega$	369.9	20.2%
100 $\Omega$	100 $\Omega$	10 $\Omega$	10 $\Omega$	349.5	5.5%
100 $\Omega$	10 $\Omega$	10 $\Omega$	10 $\Omega$	348.5	0.3%
10 $\Omega$	10 $\Omega$	10 $\Omega$	10 $\Omega$	348.5	0.0%

Color highlighted cells are referring to towers' enhanced footing resistance.

**Table 6.** Impact of reducing towers footing resistance 5  $\Omega$  on FFO.

Twr4_FR	Twr3_FR	Twr2_FR	Twr1_FR	Vt at S/S (kV)	PMOD (%)
100 $\Omega$	100 $\Omega$	100 $\Omega$	5 $\Omega$	303.7	34.4%
100 $\Omega$	100 $\Omega$	5 $\Omega$	5 $\Omega$	283.1	6.8%
100 $\Omega$	5 $\Omega$	5 $\Omega$	5 $\Omega$	282.7	0.1%
5 $\Omega$	5 $\Omega$	5 $\Omega$	5 $\Omega$	282.7	0.0%

Color highlighted cells are referring to towers' enhanced footing resistance.



**Figure 12.** Switchgear FFO with 5  $\Omega$  footing resistance in the first tower.

Conclusively, the enhancement of earthing resistance for the first adjacent tower to the substation is very effective to reduce the transient overvoltage due to a back-flashover. There is no need to spend any money enhancing the other towers' footing resistance as the reduction in FFO due to the reduction in other towers' footing resistance is ineffective.

#### 4.2. Case B: Impact of Reducing SA Earthing Resistance (SA\_ER) on FFO

Typically, the SA is grounded via substation grounding resistance (S/S\_R). In this study, S/S\_R varied between 1  $\Omega$  to 5  $\Omega$ , and hence, the SA\_ER varied in the same range.

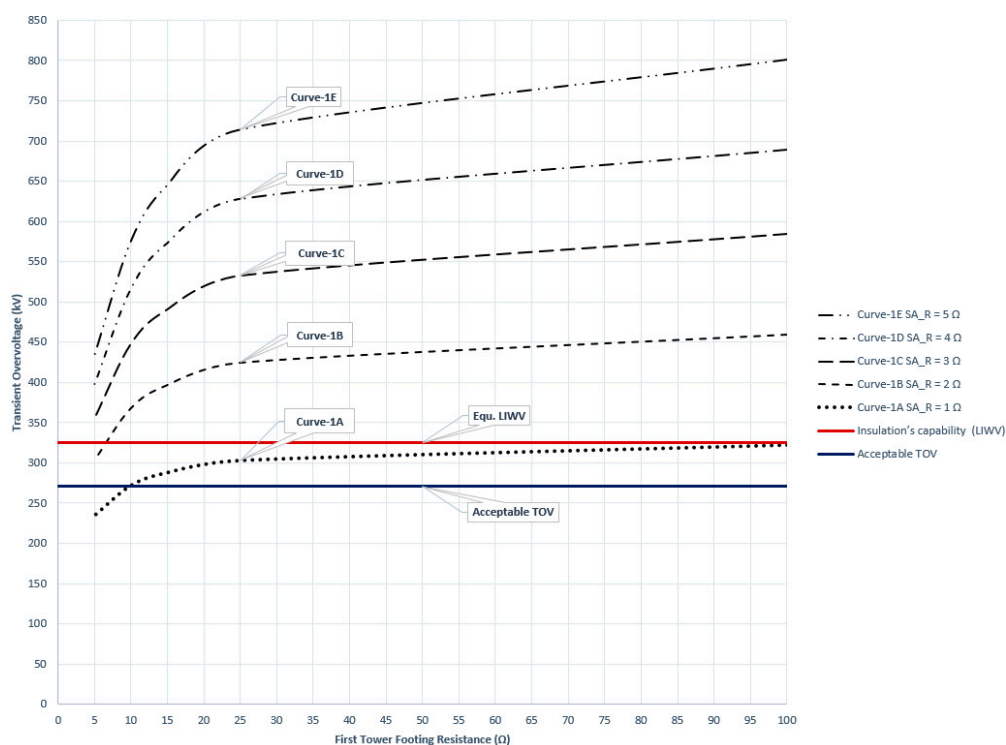
The FFO was calculated during the back-flashover using PSCAD/EMTDC program at substation terminal with different SA earthing resistance (SA\_ER). The base case for this study was done where the towers' footing resistance was assumed to be constant at 100  $\Omega$  for all the towers. The results are given in Table 7. The acceptable value (270 kV) for FFO was obtained with a very small SA\_ER. This low value of earthing resistance has many constraints:

- Very low resistance values in most substations are very expensive, which will affect the total cost of the grounding system.
- The grounding resistance of substation may vary with high values in the dry season due to the variations in the soil's electrolytic content and temperature [45].
- Very low grounding resistance values may result to increase probabilities for surge arrester damage due to the high discharged currents flowing through them and energy absorption capability [19].

**Table 7.** Variation of Substation FFO due to FFBF with SA earthing resistance.

SA_ER	Vt at S/S (kV)
5 $\Omega$	801
4 $\Omega$	698
3 $\Omega$	585
2 $\Omega$	460
1 $\Omega$	322
0.65 $\Omega$	270

Figure 13 shows the FFO variation at different SA\_ER values but with the variation of the first tower footing earthing resistance as well. The  $x$ -axes show the first tower footing resistance and the corresponding calculated FFO is shown on the  $y$ -axes at 1, 2, 3, 4, and 5  $\Omega$  for SA earthing resistance. All remaining towers' footing resistance is assumed to be constant at 100  $\Omega$  for all other towers. Figure 13 shows that the measured voltage at the substation terminal goes below the acceptable FFO value only with 1  $\Omega$  SA (better than 0.65  $\Omega$ ) if the first tower footing resistance is less than 5  $\Omega$ .



**Figure 13.** FFO against first tower footing resistance at different SA\_ER from (1–5  $\Omega$ ).

#### 4.3. Case C: Impact of Reducing Both First Tower Footing Resistance and SA Earthing Resistance on FFO

The risk of a back-flashover can be reduced by keeping the tower foot impedances to a minimum, particularly close to the substation (first five to seven towers) [20]. In this study, the first tower footing resistance, and the SA earthing resistance were reduced. While all other towers footing resistance were maintained at 100  $\Omega$ .

Table 8 shows that a value of 2.87  $\Omega$  for both SA\_ER and Twr1\_FR is enough for the FFO to go below the acceptable setting (270 kV FFO) at the substation terminal.

**Table 8.** Impact of reducing the Twr1\_FR and SA\_ER on FFO.

Twr1_FR	S/S_R	Vt at S/S (kV)
5 $\Omega$	5 $\Omega$	433
4 $\Omega$	4 $\Omega$	356
3 $\Omega$	3 $\Omega$	279
2.87 $\Omega$	2.87 $\Omega$	270
2 $\Omega$	2 $\Omega$	205

Case B achieved a value of FFO equal to 270 kV at SA\_ER = 0.65 ohms, while case C achieved the same value of FFO at earthing resistance of both Tw1\_FR and SA\_ER = 2.87  $\Omega$ .

Although an acceptable FFO can be achieved with an unattainable grounding resistance as case B, it can be obtained with an achievable value of grounding resistance as illustrated in case C.

So, case C represents an economic solution since a very low resistance value for substations is unattainable due to high soil resistivity and seasonal effect.

#### 4.4. Economical Comparison Study

An economical comparison study is presented for case B and case C. The potential rise due to back-flashovers at the substation terminal is 270 kV in Case B when the substation grounding is enhanced to 0.65  $\Omega$ . The potential rise due to back-flashovers at the substation terminal is 270 kV in case C when both first tower footing resistance and SA grounding system is 2.87  $\Omega$ .

For the economic study, the following typical data were assumed:

- The soil resistivity for the first layer is 300  $\Omega\text{m}$ .
- The depth of the first layer is 2 m.
- Soil resistivity for the second layer is 100  $\Omega\text{m}$ .
- The conductor used for the grounding system is 120 Sq.mm, copper, annealed soft-drawn.
- The cost/meter for 120 mm<sup>2</sup>, copper, annealed soft-drawn is assumed to be 17 USD as per [46].
- The rod used for the grounding system is 2 cm diameter, 10 m length, copper-clad steel rod.
- The cost of the one rod is assumed 100 USD as per [46].

Two studies were conducted using ETAP [47] software as shown in Table 9.

Obviously, from Table 9, enhancing both SA\_ER and Twr1\_FR results in a noticeably lower cost compared to enhancing SA\_ER only. More than 75% cost saving by using the proposed technique for controlling the FFO via enhancing the first tower footing resistance.

#### 4.5. Impact of Bonding the First Tower Earthing System with Substation Earthing System

Practically, the first tower is located at a short distance to the substation. There are two different methods for connecting the towers lightning protection system earthing resistance (tower footing resistance or ground wire) and substation grounding grid as follows:

1. It may be connected through the connection of the guard protection wire (GW) or OPGW (optical ground wire) to the gantry grounding system [48,49]. References [48,49] illustrate the different ways of grounding the guard protection wire/OPGW with the substation earthing mat.

2. Footing resistance of the first adjacent tower to the substation may be connected to the substation grounding system via two underground buried conductors or via extending the substation grounding grid along the route of the incoming lines [8,23,50].

**Table 9.** Economical comparison study between enhancing SA\_ER only VS enhancing both SA\_ER and Twr1\_FR.

Cases	ETAP Cost Calculation						Total Cost \$	Rg	Total Fixed Cost
	Conductor			Rod					
Case B Enhancing SA_ER Only	Total No.	Total Length m	Cost \$	Total No.	Total Length m	Cost \$			
		11	820	13,940.00	61	610	6100.00	20,040.00	0.65 Ω
	For SA_ER								
Case C Enhancing of Both SA_ER and Twr1_FR	Conductor			Rod			Total Cost \$		
	Total No.	Total Length m	Cost \$	Total No.	Total Length m	Cost \$		2.87 Ω	4880 \$
	4	120	2040.00	4	40	400.00	2440.00		
	For Twr1_FR								
	Conductor			Rod			Total Cost \$		
	Total No.	Total Length m	Cost \$	Total No.	Total Length m	Cost \$			
	4	120	2040.00	4	40	400.00	2440.00		

The bonding between the earth system of the lightning protection system and the equipment grounding system is highly recommended as per the National Electrical Code (NEC). Otherwise, the equipment will be exposed to damage due to ground potential differences [51]. However, when a lightning strike hits a large-scale grounding system, it causes electrical stress on the relatively long circuits. Consequently, the ground potential rise will be investigated due to lightning strikes at different points of the such-large scale grounding system. The lightning stroke current is very large (up to 200 kA). This huge current may cause a huge ground potential difference on the earthing grid and excessive stress to the equipment insulation [52].

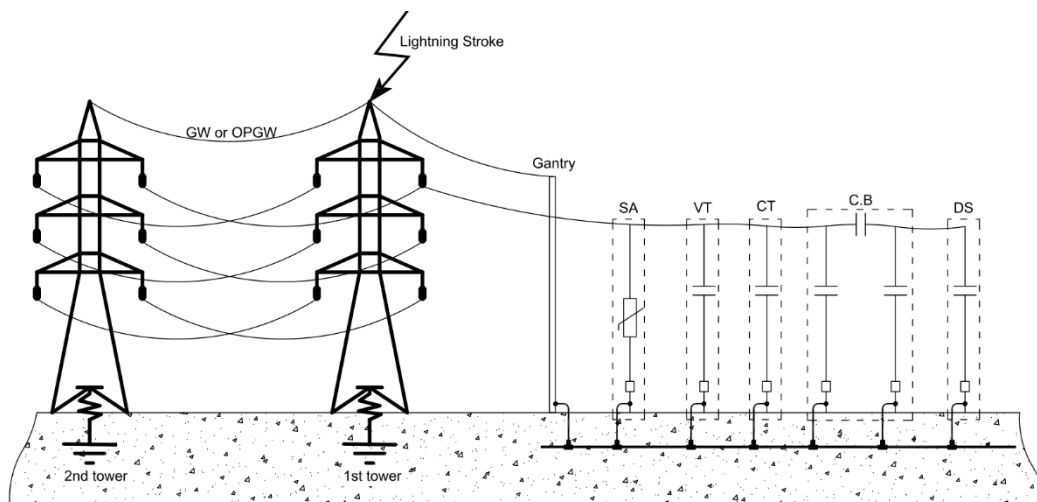
The two above methods were simulated using PSCAD software. GW and OPGW were simulated by its surge impedance and velocity of propagation. The buried ground conductor was modeled using PSCAD with its equivalent π circuit. The resistance R and the self-inductance L were connected in series, whereas the transverse conductance G and the capacity C, connected in parallel [53,54].

In this study, the earthing systems of the first tower and the SA were bonded to the substation earth mat via the two above-described methods, whereas all other towers footing resistance were maintained at 100 Ω. Figure 14 shows the front view for the interconnection between the towers' earthing system and the main substation components earthing system.

The direct connection between towers' lightning protection earthing system and substation grounding system dramatically improves the FFO across the substation insulators. The applied voltages across the insulators are within the acceptable limit, i.e., less than 270 kV. Using method No. 1, the FFO across insulators is 143 kV while it reaches 148 kV using method No. 2.

Meanwhile, the interconnection (while keeping the tower footing resistance with a high resistance value) improved the FFO across the insulators, but the ground potential rise (GPR) of both earthing systems become too high. A huge amount of the lightning current was discharged to the lowest grounding system i.e., to the substation earthing system through the interconnection conductors. This led to a high ground potential rise on the substation earthing system. Also, the high footing resistance leads to a high GPR on the tower footing. Table 10 shows GPR at Twr-1, GPR at S/S, and FFO during the two methods of interconnection between the Twr-1 and S/S earthing systems without improving the first tower footing resistance. Table 11 illustrates these values with improving the first tower footing resistance.





**Figure 14.** Interconnection between towers earthing system and substation earthing system, S/S component equivalent capacitance, and its connection to the grounding system.

**Table 10.** Ground potential rise (GPR) and FFO during the interconnection between the Twr-1 and S/S earthing systems without improving the Twr1\_FR.

Interconnection Methods	GPR on the Twr-1 (kV)	GPR on the S/S (kV)	FFO Across Insulators (kV)
Method-1	1290	477	143
Method-2	1350	508	148

**Table 11.** GPR and FFO during the interconnection between the Twr-1 and S/S earthing systems with improving the Twr1\_FR.

Interconnection Methods	GPR on the Twr-1 (kV)	GPR on the S/S (kV)	FFO Across Insulators (kV)
Method-1	396	227	112
Method-2	420	173	131

Conclusively, the enhancement of earthing resistance for the first adjacent tower to the substation is very effective to reduce the GPR due to a back-flashover. The interconnection between the lightning protection earthing system and substation earthing system is very effective to reduce the FFO across the insulators.

## 5. Conclusions

The effect of enhancing the earthing resistance of surge arrester and first tower adjacent to the substation during fast front back-flashover was investigated. The results show that the higher the earthing resistances for SA and the first tower, the higher the calculated transient overvoltage at the substation terminal. When the earthing resistances for the first tower only is decreased while all other towers earthing resistance are kept at high values, the value of calculated transient overvoltage at the substation terminal is reduced to the acceptable limits. The reduction in SA earthing resistance is also effective to make a significant reduction in the calculated transient overvoltages at the substation terminal; however, it may be achieved by a very low resistance which is not economically or practically justified due to high soil resistivity and the high cost of the grounding system. Also, the very low resistance value for SA may result in damage due to the limit of the energy absorption capability. The most effective method to achieve a proper value of FFO, to reduce the risk of a back-flashover and reduce the applied GPR on tower footing and substation grounding grid is achieved by enhancing the first tower footing resistance and bonding with the substation earth grid.

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