Back-flashover Investigation of HV Transmission Lines Using Transient Modeling of the Grounding Systems

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Abstract: The article presents the transients analysis of the substation grounding systems and transmission line tower footing resistances which can affect to the back-flashover (BF) or overvoltage across insulator chain in an HV power systems by using EMTP-RV software. The related transient modeling of the grounding systems is based on a transmission line (TL) model with considering the soil ionization. In addition, different configuration of grounding system have been simulated to calculated the BF, including number of vertical grounding rod, length of rod, point of lightning current injection into the grounding grid and using two depth design of grounding system where the surface of substation under consideration is very small orit is necessary to bury the grounding grid in the rocky media, occasionally. The simulation results have shown that how the mentioned parameters can considerably affect inception of BF, and suitable design of grounding system can reduce damages caused by lightning.

1 Introduction

Transmission lines are most important, vulnerable and sensitive components of the power system which may be encountered with the environment phenomena such as the lightning strokes. The lightning overvoltage may be caused line insulation breakdown, due to occurrence of the BF phenomenon [1-2]. When lightning strikes a tower or a ground wire, a traveling voltage is generated which travels back and forth along the tower, being reflected at the tower grounding system. Consequently, the transient ground potential rise (TGPR) have been created at the line towerand the cross-arms. This transient over voltages cause stresses across the insulator chains. Whenever this transient voltage exceeds thewithstand voltage level, flashover will occurs. Such flashover is named BFas the voltage at the tip of cross arm becomes larger than the voltage of line conductor. Therefore, the BF voltages are generally generated by multiple reflections along the tower under stroke. The maximum magnitude of transient induced voltage caused by lightning will be directly proportional to the peak of lightning stroke current [3].

In general, the BF forecast is a very complicated task due to it depends nonlinearly on different parameters such asthe positions of phase conductors and guard wires of transmission line, line towers and tower footing grounding systems, soil ionization, insulator chains and etc. It is necessary to mention that to predict the back-flashover, exactly, all of components at the HV power system must be properly modeled in transient regime. In [4-6] the authors have already describedand validated a simplified resistive model, able to simulate the ground potential rise (GPR) of typical tower grounding systems. [7, 8] have simulated the grounding system as a Pi-circuit model innon-linear conditions. In [9], the Pi-circuit groundingsystem model is implemented in an ATP-EMTP 150 kV–50 Hzmodel for BF simulation.

In this paper, the transient model of subsystems in HV power system have been proposed and investigated in the EMTP-RV software in order to propose an accurate prediction of BF. Grounding systems of substations and towers, as the most important components of the power system, have been modeled by lossy transmission lines method (TLM) considering soil ionization under lightning impulse. According to the simulation results, considering different states such as grounding system arrangement, point of impulse injection and etc. have contributions on the inception of BF, time plots of the insulator chain voltage and transient ground potential rise. Results show that the proposed procedures can be

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used to accurately predict the maximum transient voltage at the cross-arms of the towers which results in a BF across an insulator chain.

2 Transient Modeling of Power System Components

In this section, modeling of different components for a power system is proposed in transient regime caused by lightning strokes.

2.1 Modeling of Lightning, Transmission Line and Tower

A 1000 kV double circuit transmission line have been considered to study the transient behavior of a power system against the lightning strokes. The span length of related transmission line is 500 m. Phase conductors and guard wires of transmission line were simulated by means of "Jmarti" frequency-dependent model in EMTP_RV.

The tower configuration and its impedance model have been shown in Fig.1. Modeling of transmission line tower is based on multistory model where consists of main legs and cross-arms [10-11]. Also the impedance values of tower model have been given in Table 1.

Lightning current is modeled by the proposed model of CIGRE as an impulse current source with waveform 100 kA/3μsas shown in Fig. 2.
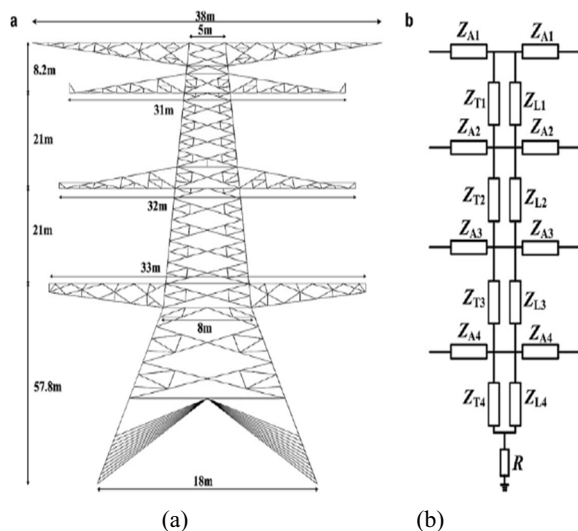

Fig. 1.(a) The tower under consideration and (**b**) its impedance model.

Table 1 Impedance value of the tower model [4].

K	$Z_{Ak}(\Omega)$	$Z_{Tk}(\Omega)$	$Z_{Lk}(\Omega)$
1	307	142	1287
2	313	135	1215
3	298	117	1053
4	280	80	720

2.2 Grounding System Model

Tower footing grounding system has been assumed as a resistance, 10 ohm, to investigate the transmission line and tower behavior against lightning stroke, frequently. Though this procedure is useful to assess voltage and current waveforms along the transmission lines, but it cannot be used for accurate calculation of transientsignals due to neglecting the capacitive, inductive and conductive characteristics of grounding systems. Moreover, using the grounding system with different configuration for towers create a variety impedance value which must be considered by the related models. Many high frequency models have been presented for the grounding system of tower footing systems. Equivalent resistance of the vertical and horizontal electrode can be calculated by Eq. (1) and Eq. (2), respectively [12].
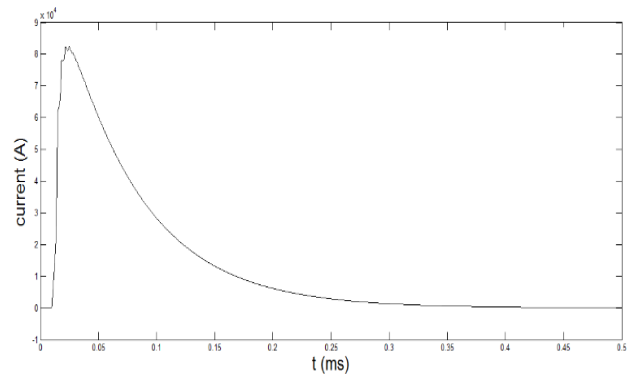

Fig. 2 Typical waveform of lightning current.

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

and

$$R = \frac{\rho_s}{\pi \cdot l} \left[\ln \left(\frac{2 \cdot l}{\sqrt{2} \cdot a \cdot h} \right) - 1 \right] \tag{2}$$

where h, l, a and ρ_s are buried depth (for the horizontal electrode), length , radius of electrode (m) and the soil resistivity (Ω.m), respectively.

One of the most accurate methods to simulate the grounding system in transient regime is TLM (transmission line method). This method is a numerical technique, which can be used to both in the time and in the frequency domains [13].

In high frequency analysis under lightning stroke, the soil ionization is an important phenomenon that must be considered in the modeling of grounding systems. This phenomenon can be represented by a set of cylindrical zones around the electrode as shown in Fig. 3a.

According to [13], in Fig. 3b, time-variable resistive and conductive components for the grounding electrode must be considered in order to contain the soil

ionization effects. Therefore, Eq. (3) to Eq.(5) can be used to calculate time-variable resistive component for both horizontal and vertical electrodes which can simulate the soil ionization and skin effects. It is necessary to mention that the skin effect has been considered by using coefficient $\delta = \sqrt{\frac{2 \cdot \rho_c}{\omega \cdot \mu}}$ in Eq. (5) where $f = 500\ KHz$.
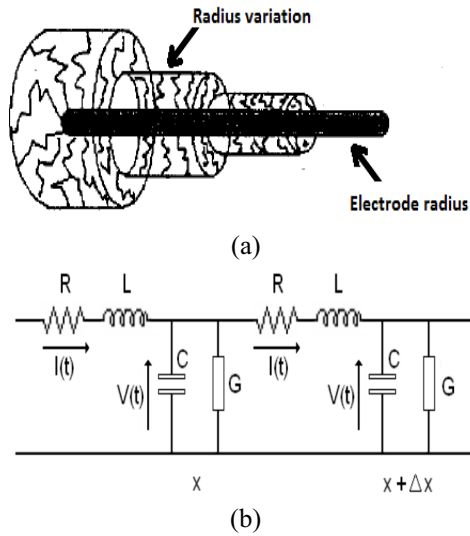

(a)

(b)

Fig. 3. (a) Representation of the soil ionization around an electrode, (b) Modeling of grounding electrode [13]

$$R(t) = R_T \cdot \frac{1}{\sqrt{1+\frac{I(t)}{I_g}}} \quad (\Omega) \tag{3}$$

where I(t) is the lightning current passing through grounding electrode and Ig is the critical current which makes the soil ionization as shown in Eq.(4). Also Ecr is the critical electric field and has been considered as 300 kV/m.

$$I_g = \frac{E_{cr} \cdot \rho_s}{2 \cdot \pi \cdot R_T^2} \quad (A) \tag{4}$$

and

$$R_T = \frac{\rho_c \cdot \Delta x}{2 \cdot \pi \cdot a \cdot \delta} \quad (\Omega) \tag{5}$$

Eq. (6) and Eq. (7) are used to compute the conductive component of the vertical and horizontal electrode, respectively [13]. In addition Δx is the length of segment of an electrode in m.

$$G(t) = \frac{2 \cdot \pi \cdot \Delta x}{\rho_s \cdot \ln(\frac{2 \cdot l}{a})} \cdot \sqrt{1 + \frac{I(t)}{I_g}} \quad (\mho) \tag{6}$$

$$G(t) = \frac{2 \cdot \pi \cdot \Delta x}{\rho_s \cdot [\ln(\frac{2 \cdot l}{\sqrt{2 \cdot h \cdot a}})-1]} \cdot \sqrt{1 + \frac{I(t)}{I_g}} \quad (\mho) \tag{7}$$

where ε_r is the air permittivity (F/m) and ρ_c is the conductor resistivity (Ω.m). Also the capacitive and inductive components of the vertical grounding electrode have been calculated by the following equations.

$$C = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_r \cdot \Delta x}{ln(\frac{2 \cdot l}{a})} \quad (F) \tag{8}$$

and

$$L = \frac{\mu_0 \cdot \Delta x}{2 \cdot \pi} \cdot \ln\left(\frac{2 \cdot l}{a}\right) \quad (H) \tag{9}$$

In addition, Eq. (10) and Eq. (11) can be used to obtain the parameters of the horizontal electrode.

$$C = \frac{2 \cdot \pi \cdot \varepsilon_0 \cdot \varepsilon_r \cdot \Delta x}{ln(\frac{2 \cdot l}{\sqrt{2 \cdot h \cdot a}})-1} \quad (F) \tag{10}$$

and

$$(H)L = \frac{\mu_0 \cdot \Delta x}{2 \cdot \pi} \cdot \left[\ln\left(\frac{2 \cdot l}{\sqrt{2 \cdot h \cdot a}}\right) - 1\right] \tag{11}$$

2.3 Modeling of the power system under study by EMTP_RV

BF simulations have been carried out by considering a long overhead transmission line as mentioned in section A. In this study, it has been assumed that lightning stroke hits to the first tower. Fig. 4 shows the simulated power system with considering a horizontal/vertical grounding electrode by EMTP_RV.

As shown in Fig. 5, transient voltages on tower corresponding to the cross-arms of g1 and g2 have the highest values caused by lightning stroke. The voltage across the insulator chain is found by subtraction of voltage of tower and phase voltage at any instant. It is necessary to mention that the maximum transient voltages across the insulator chain will be produced by "maximum voltage at tower+ maximum phase voltage" in the worst condition.

3 Comparison and Validation

The obtained results of the simulation in EMTP_RV and Ref. [4] have been compared and validated to the depicted resulted in Fig. 6. In this study, lightning current passing through the different transmission line towers such as tower under direct lightning stroke and adjacent towers have been measured and compared to Ref. [4] as shown in Table 2.
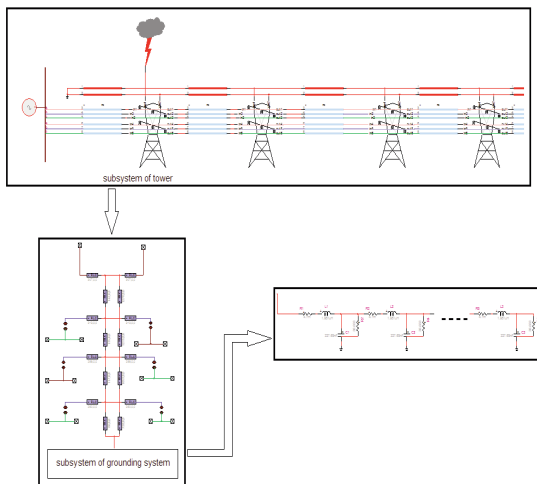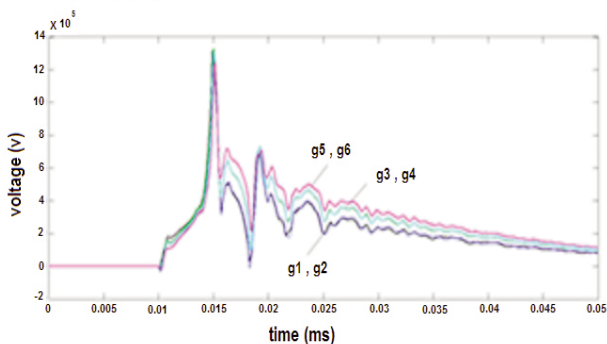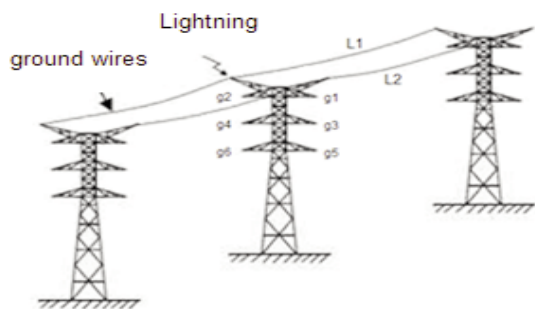
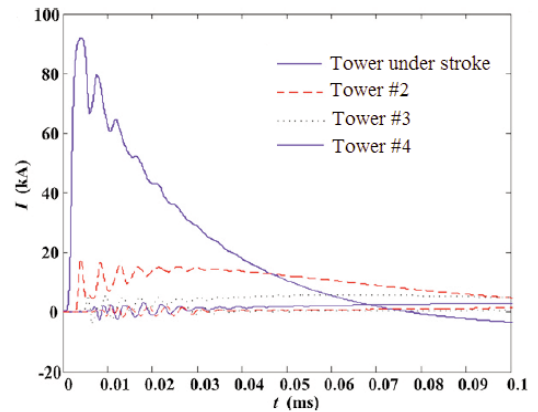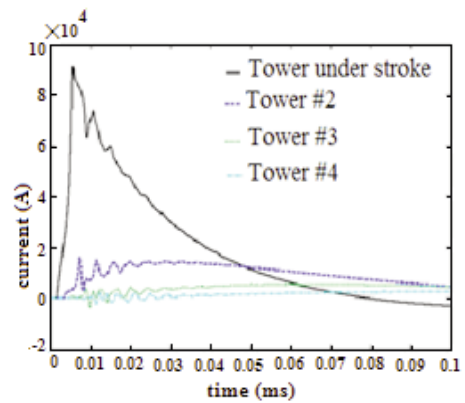**Fig. 4** Simulated power system under consideration.

Fig. 5 Induced over voltages on tower at different points

(a)

(b)

Fig. 6 Lightning current waveform on towers. (a) Ref. [4] and (b) Simulation results

4 Simulation Results and Discussions

4.1 Calculated over voltage across g2 with different segmentation

In order to compute the maximum over voltage across the insulator chains, grounding system modeling has been carried out by TLM. In this model, at first grounding conductor must be divided to several segments. Then each of segments has been substituted by a presented model in section 2. In this study, grounding conductor radius and buried depth are 0.0125m and 0.5m, respectively; and $\rho_c = 1.7241 \times 10^{-8} \, \Omega$ m, $\varepsilon_r = 10$ and $\rho_s = 100 \, \Omega \, m$.

Fig. 7 shows the effect of the number of segments on the calculated over voltage across the insulator chains for a vertical and horizontal grounding electrode with the length of 20 m. Obviously, the related over voltage can be accurately calculated with proper choice of the segment length (Δx).
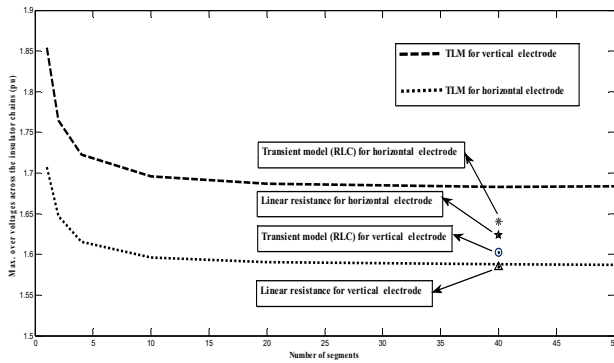
Fig. 7 Calculated over voltage across g2 with respect to the number of segments

According to the obtained results, the induced over voltage across the insulator chains with considering a linear resistance for a horizontal and vertical grounding electrode with the length of 20 m have -%2.28 and %5.8 errors, respectively, with respect to using TLM for grounding electrodes. Implementing high-frequency lumped RLC circuit models (as introduced in [12]) for horizontal or vertical grounding electrodes also have -%3.36 and %4.77 errors, respectively. The errors are significant, thus, TLM model is the best one for overvoltage studies. According to the presented results in Fig. 7, where the results converge, optimum segmentation can be found for accurate calculation of the maximum induced over voltages.

4.2 Effect of Soil ionization phenomenon on BF

Effect of considering soil ionization phenomenon in the proposed model for calculating maximum over voltage across the insulator chains has been presented in Table 3; both for vertical and horizontal grounding electrodes with different segment lengths and with the same data in the previous section.

Table 2 Comparison between obtained lightning current passing through towers in kA by [4] and simulation

Tower footing resistance	Comparison between	Tower under strike	Tower #2	Tower #3	Tower #4	Tower #5	Tower #6
10 Ω	Ref. [4]	91.8	17.8	5.5	2.9	1.9	1.3
	Simulation results	91.1	16.3	5.5	2.6	1.7	1.1
Error (%)		**0.6**	**8.4**	**0**	**10.3**	**10.5**	**15.3**
20 Ω	Ref. [4]	84.7	17.9	7.3	3.8	2.2	1.4
	Simulation results	83.2	17.3	7.2	3.8	2.2	1.3
Error (%)		**1.7**	**3.3**	**1.3**	**0**	**0**	**7.1**
30 Ω	Ref. [4]	78.6	18.9	8.2	4.5	2.8	1.8
	Simulation results	76.5	18.2	8.1	4.5	2.8	1.8
Error (%)		**2.6**	**3.2**	**1.2**	**0**	**0**	**0**
40 Ω	Ref. [4]	73.4	19.1	8.8	5	3.2	2.1
	Simulation results	70.9	18.7	8.6	4.9	3.1	2.1
Error (%)		**3.4**	**2**	**2.2**	**2**	**3.1**	**0**
60 Ω	Ref. [4]	64.7	19.5	9.5	5.6	3.7	2.5
	Simulation results	61.8	18.9	9.3	5.5	3.6	2.6
Error (%)		**4.4**	**3**	**2.1**	**1.7**	**2.7**	**0**

As expected, the soil ionization has a significant influence on the produced potential across the insulation chain. The results presented in Table 3 conclude that ignoring soil ionization, especially where soil resistivity increases for example in rocky soils, will result in highly overdesigned plans for tower footing grounding systems.

4.3 Grounding system under study with different configuration

In order to compare and discuss about the influence of the configuration of the grounding system on BF under fast transients as a lightning stroke, grounding systems with vertical rods have been considered and simulated as shown in Fig. 8. This grounding system has formed by the mesh of 6m×6m which are buried in the soil at 0.5m depth and has been modeled by using TLM.
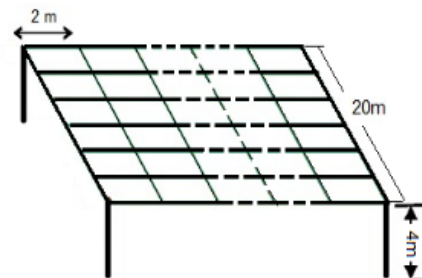

Fig. 8 Grounding system under study

In sequel, the effect of different parameters on maximum over voltage across insulator chains have been investigated and discussed.

4.3.1 The effects of number and length of the vertical rods

Number of vertical rods as well as their length has no significant effect on the maximum over voltage as shown in Tables 4 and 5.

Table 3. Effect of soil ionization on the maximum over voltage across the insulation chain

ρ_s ($\Omega.m$)	Type of grounding electrode	Segment length [m]	20	10	5	2	1	0.5	0.25
100	Vertical	Without soil ionization [pu]	1.854203	1.765273	1.723024	1.695611	1.686635	1.683066	1.684941
		With soil ionization [pu]	1.722965	1.595354	1.525714	1.474365	1.453043	1.440979	1.434067
		Difference (%)	**-7.1**	**-9.6**	**-11.5**	**-13**	**-13.8**	**-14.4**	**-14.9**
	Horizontal	Without soil ionization [pu]	1.707678	1.647053	1.615954	1.596201	1.590187	1.587657	1.586242
		With soil ionization [pu]	1.623021	1.541322	1.493656	1.458008	1.443708	1.435612	1.431081
		Difference (%)	**-4.9**	**-6.4**	**-7.6**	**-8.6**	**-9.2**	**-9.5**	**-9.8**
1000	Vertical	Without soil ionization [pu]	2.6444517	2.602096	2.582384	2.569786	2.566592	2.565202	2.562766
		With soil ionization [pu]	1.739742	1.611203	1.540566	1.487363	1.464408	1.450586	1.442082
		Difference (%)	**-34.2**	**-38.1**	**-40.3**	**-42.1**	**-42.9**	**-43.5**	**-43.7**
	Horizontal	Without soil ionization [pu]	2.311695	2.271605	2.257443	2.244842	2.239658	2.241310	2.239627
		With soil ionization [pu]	1.640134	1.556608	1.507553	1.469839	1.453805	1.444055	1.438029
		Difference (%)	**-29.1**	**-31.5**	**-33.2**	**-34.5**	**-35.1**	**-35.6**	**-35.8**
2000	Vertical	Without soil ionization [pu]	3.240917	3.130288	3.109214	3.074433	3.081416	3.116214	3.082942
		With soil ionization [pu]	1.749846	1.620384	1.548779	1.494175	1.470149	1.455361	1.446129
		Difference (%)	**-46**	**-48.2**	**-50.2**	**-51.4**	**-52.3**	**-53.3**	**-53.1**
	Horizontal	Without soil ionization [pu]	2.710763	2.683562	2.670179	2.662341	2.657103	2.658418	2.654417
		With soil ionization [pu]	1.650597	1.565274	1.515045	1.475910	1.458944	1.448245	1.441550
		Difference (%)	**-39.1**	**-41.7**	**-43.3**	**-44.6**	**-45.1**	**-45.5**	**-45.7**

Table 4 Number of rods versus maximum voltage

Number of rods	Maximum Voltage [pu]
0	1.432315
4	1.431538
8	1.431418
20	1.430909
40	1.429505

Table 5 Length of rods versus maximum voltage

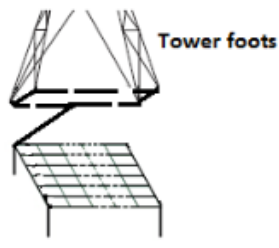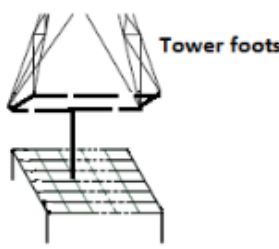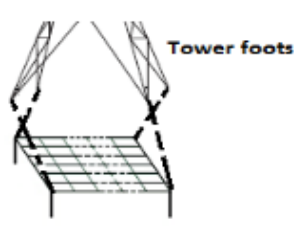| Length of rods [m]	Maximum Voltage [pu]
2	1.431769
4	1.431538
6	1.431382
8	1.431241
10	1.431119

4.3.2 Influence of impulse injection point on maximum voltage

Impulse injection point to grounding system at tower footing is very important to calculate initiation voltage of BF. In general, the injection position has been categorized to three types as shown Table 6.

The results have been presented in Table 7 for the mentioned types of injection point. As shown, for the same grounding system, the maximum voltage on a tower for injection point at the center is smaller than that for injection point at the comer. In the case of injection point at the corner, the inductance of conductors will be considerable and will prevent the current passing through the grounding system towards other directions. But the case of injection point at the center makes the grounding system to show small inductive effect. Therefore, using Type 2 is recommended instead of Type 1. Also the obtained results show that the induced maximum voltage on a tower has the lowest value for Type 3, which is the best type of injection point.

**Table 6** Connection form of tower foots to grounding system

Type 1	
Type 2	
Type 3	

Table 7 Connection point versus maximum voltage

Case study	Maximum voltage [pu]
Type 1	1.448437
Type 2	1.437178
Type 3	1.431538

4.4 Grounding system design in rocky surfaces by using TLM

In general, some limitations such as rocky areas where the towers are spotted, limitation of required area for grounding installation, dry soil and other geological factors may make undesirable and unsafe installed grounding system. Two-story grounding system design is one of the proposed methods to obtain a safe voltage as shown in Fig 9.
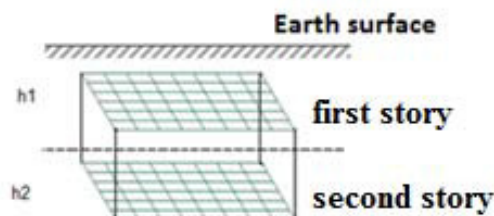
Fig 9 Two-story grounding system.

Table 8 shows the maximum voltage across insulator chain for a conventional horizontal grounding system and two-story grounding system with h1=0.4m, h2=0.8m and four vertical rods with having length of 0.4m.

Table 8 Comparison between two types of grounding systems $(20 \times 20 \text{m}^2)$

Grounding system type	Maximum voltage [pu]
A conventional horizontal grounding system	1.516496
Two-story grounding system	1.468332

Table 9 depicts the equivalent two depth grounding network which can be substituted by a conventional grounding system with larger dimensions. Therefore this design is suitable for rocky areas, dry soil and etc.

Table 9 Comparison between extended grounding systems

Grounding system Type	Maximum voltage [pu]	Dimensions [m×m]
A conventional horizontal grounding system	1.513878	20×20
Two-story grounding system	1.523755	8×10

5. Conclusion

Using a proper grounding system and an accurate transient modeling of tower footing grounding grid have significant effect on the maximum induced voltage caused by lightning stroke across the insulator chains. The obtained results showed that the soil ionization phenomenon has considerably contribution on the inception of BF occurrence. Moreover, current injection point to tower footing grounding system shows that the

choosing Type 3 for connection is a better scenario rather than lowering the probability of the BF initiation.

Furthermore, applying two-story design for grounding system (suitable for rocky areas) has shown lower over voltages.

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