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The Lightning Protection Assessment of Distribution Lines with Considering Frequency Grounding System

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Abstract: Ensuring the protection of all components within power systems from lightning-induced overvoltage is crucial. The issue of power interruptions caused by both direct and indirect lightning strikes (LS) presents significant challenges in the electrical sector. In medium voltage distribution feeders, the relatively low dielectric strength makes them susceptible to insulation degradation, which can ultimately lead to failures in the distribution system. Therefore, implementing effective protective measures against LS is vital for maintaining an acceptable level of reliability in distribution systems. This paper presents an analytical assessment of LS-induced system overvoltage through high-frequency modeling of components within a 20kV distribution system. The study utilizes EMTP-RV software for precise component modeling, including the grounding system, surge arresters, and distribution feeders. Additionally, the operational impacts of protective devices, such as ZnO surge arresters, shield wires, and lightning rods, are evaluated to mitigate LS-induced overvoltage. To analyze the grounding system's influence on LS-induced overvoltage, a frequency grounding system is implemented using the method of moments (MOM). Furthermore, eight different scenarios are explored to assess the anti-LS capabilities of the 20kV distribution system. Each scenario involves evaluating dielectric breakdown and overvoltage across the insulator chain while proposing suitable protective solutions. The results indicate that the absence of shielding wires and surge arresters leads to higher breakdown voltages, with the lowest breakdown voltage occurring when surge arresters are installed during LS events. Additionally, the use of a frequency grounding system, due to its accurate modeling, yields more precise results compared to a static resistor approach. The MOM simulation reveals a 50% reduction in breakdown voltage under the worst-case scenario, and overall overvoltage experiences a 2% decrease.

Keywords: Distribution System, Frequency Grounding System, Lightning Overvoltage, Surge Arrester.

1 Introduction

Distribution systems are of significant sections of the power systems due to great role of secure electricity service to the customers. Such system is seriously exposed to natural phenomenon of lightning strike (LS) due to the electrical discharge caused by the clouds' collision. The overvoltage caused by the LS can potentially lead to damage to the distribution system

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components and people as well as reduce the system reliability. Hence, protection of such vulnerable system against the inevitable LS aiming to enhance the system reliability level should be of a great concern in the planning/operation frameworks [1].

The lightning can strike the phase conductor (direct strike) or to the shield wire/lightning rod (indirect strike). The direct strike leads to the electrical discharge in the distribution system and so performance of the protection system while the indirect strike is transmitted to the grounding system, through the guard wire and lightning rod, and then reflected to the towers leading to back flashover in the distribution system. It is evident that an effective protection strategy is required to prevent the extensive failure in the system components and so improve the reliability level. Generally, the LS protection system is divided to internal and external methods [2]. In the internal protection, the LS effects, electrical fields originated by the lightning current and mechanical forces imposed to the electrical circuits and metallic components are potentially decreased. For instance, the surge arresters are of such protective devices to realize these targets. In the external protection, the lightning rods are installed nearby the system components to absorb the lightning and transmit it to the grounding system. Hence, a reliable external protection mechanism is so significant in the substations' technical designing [3].

There are several research works associated with the protection of the distribution feeders against the LS. In [4], with the purpose of protection against the LS, installation of the surge arrester, shield wire and lighting rod on the 10kV distribution feeders are studied. The obtained results of [4] evaluate the performance of the distribution feeders located in the high-resistant soil, with and without consideration of the surge arrester and lightning rod, as well as the challenge of LS-based induced overvoltage. In [5] and [6], combination of the lightning rod and surge arrester is employed to assess the anti-LS protection of the 10kV distribution feeder. Moreover, the influence of LS overvoltage on the system insulation and failure rate of the overhead feeders is analyzed in both cases of the direct and indirect LS. Based on the achieved results presented in [5], installation of surge arrester on every distribution tower has the best protection performance with high investment cost. However, it is proved that the combinatorial performance of the surge arrester and lightning rod has better performance with medium investment cost. In [7], the anti-LS protection of the distribution feeders is studied where the lightning overvoltage considering various arrangements for the surge arresters is analytically evaluated. The operational effect of the shield wire on the anti-LS protection of the 10kV distribution feeder is taken into account in [8] where the designing parameters such as ground interval, ground resistance and shield wire position is technically evaluated. In [9], installation of the surge arrester and shield wire on the 50kV distribution system with both simple and nonlinear modeling of the grounding system is assessed. In this way, the effect of indirect LS on the real-world distribution feeders is investigated using a Monte Carlo-based statistical method. Furthermore, an accurate modeling with the aim of lightning overvoltage evaluation and so proper estimation of the surge arresters' arrangement is accomplished in [9]. The effective parameters including the ground resistance, soil type and shield wire position is considered in [10] to study the efficacy of a shield wire-oriented anti-LS protection.

Despite the valuable research works carried out in the literature, the grounding system modeling is entirely simple type or non-linear type while the accurate frequency-based modeling [11] is not seen. Since appropriate modeling of the components' behavior has a significant role in the performance of the distribution system protection, the accurate frequency-based modeling of the grounding system seems to be so essential.

In this paper, modeling of the 20kV distribution system components together with the frequency-based modeling of the grounding system is performed in the EMPT-RTV software. Also, eight anti-LS protective scenarios are operationally evaluated. According to the investigated scenarios, installation of the surge arrester on the distribution towers prevents the dielectric breakdown for the insulator chain, caused by the direct LS, and also the back flashover. Moreover, using the shield wire together with the lightning rod can decrease the probability of the direct LS and also the induced voltage across the insulator chain. A low resistance grounding system is mandatory for the optimal performance of the shield wire and lightning rod. By using the mentioned devices, the back flashover currents and consequently the induced voltage across the insulator chain are alleviated. The obtained simulation results illustrate the reduction in the overvoltage across the insulator chain (for all scenarios) and also in back flashover currents (in some scenarios) by using the frequency-based model of the grounding system instead of the static model.

2 The protective strategies

In this paper, four protective strategies to hedge the distribution system versus the LS are studied. These strategies can be individually or hybrid employed depending on the protection policies of the system. In the following, the utilized protective strategies are briefly described:

- Shield wire

Protection of the overhead distribution feeders versus the direct LS is the major role of the protection strategies. To achieve this goal, shield wires are generally employed in the distribution systems. An overhead shield wire is generally installed at the top part or on the body of the distribution tower providing the anti-LS protection for the distribution feeder [12].

- Surge arrester

A surge arrester, modeled by a non-linear resistance, is assigned for reduction in the lightning overvoltage. This device has a high internal resistance in the normal condition (i.e. no lightning) and so no current passes across it. However, the internal resistance is prominently reduced concurrent with the lightning overvoltage to transmit the lightning energy to the grounding system and also decrease the overvoltage to the basic insulation level (BIL). It is noted that a surge arrester consistent with the transient behavior of a system should be selected in the designing process. Moreover, this device is installed parallel to the under-protection systems and should be capable of satisfactory response to the worst-case situation [13-14].

- Lightning rod

Installation of lightning rod on every distribution tower can decrease the LS-based current imposed to the surge arresters. Moreover, presence of the lightning rod can alleviate the lightning energy and subsequently dielectric breakdown in the surge arresters. It is evident that an appropriate grounding system besides the lightning rods is mandatory to damp the lightning waves and prevent the back flashover phenomenon [15].

- Decreasing the tower footing resistance

When the lightning strikes the shield wire, the electric current caused by the lightning overvoltage, passes the tower footing resistance leading to the overvoltage across the insulator chain. Therefore, reduction of the tower footing resistance can significantly enhance the absorption capability of the lightning currents and so decrease the lightning overvoltage across the distribution feeder phases [16].

3 Modeling of the system components

An accurate transient stability evaluation of a power system requires a comprehensive modeling of the system components using the transient state study software. In this paper, the EMPT-RV is used to simulate and analyze the under-study distribution system.

The 20kV distribution system used for the studying of the anti-LS protection strategies possesses 11 concrete towers with 100m distance. The descriptive data along with the modeling of the simulated components within the EMPT-RV software including the lightning rod, surge arrester, and shield wire are elucidated in the following.

3.1 Lightning modeling

The first step to evaluate the effect of LS overvoltage on the distribution system is generation of the lighting waveform. The peak current, front time and tail time are three major factors in the lightning waveform generation. For the sake of LS modeling in the EMPT-RV, a CIGRE 30kA current source parallel by a 400Ω resistance, as depicted in Fig.1, is utilized to simulate the lightning channel illustrated in Fig.2. The parameters for the front time and tail time of the current have been chosen as 8 µs and 20 µs, respectively [6].

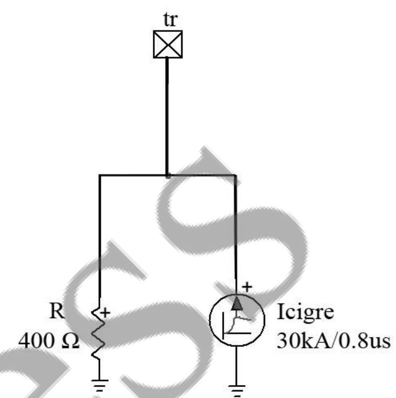

Fig. 1 The equivalent circuit generating the lightning in the EMTP-RV

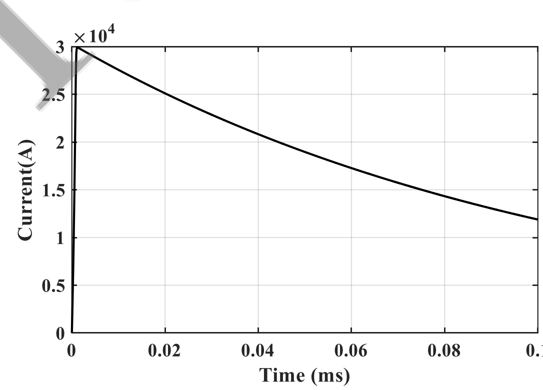

Fig. 2 The lightning current waveform simulated in the EMTP-RV

3.2 Surge arrester modeling

Surge arrester is an essential device for protecting of the distribution system against the lightning overvoltage. Transient behavior of the surge arrester nonlinearly changes based on the system specifications such as the frequency, front time of the applied waveform and the passing transient current. Thus, several frequency models such as Penciti [17], Fernandez [18], and IEEE [19], has been proposed to simulate the surge arrester performance. In this paper, the IEEE frequency model, demonstrated in Fig. 3, is utilized.

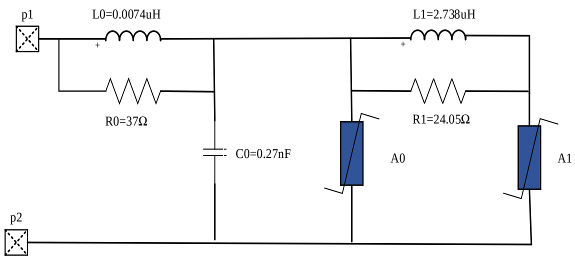

Fig. 3 Electrical model of the IEEE surge arrester

In this model, two nonlinear resistances Rn1 and Rn2 is used to model the nonlinear behavior of the voltage and current. These two resistances are separated by a RL filter. The RL filter creates low impedance in the case of LS with long wave front (i.e. Rn1 and Rn2 are parallel). On the other hand, the RL filter acts as high impedance in the case of low front waveform and most of the lightning current passes through Rn1. Moreover, the element C is used to represent the capacitance feature across the surge arrester; L1 stands for the magnetizing inductance in the vicinity of the surge arrester; R1 is used to prevent the numerical tolerance within the model implementation in the study softwares [20]. To calculate the IEEE model components, the following equations can be used:

$$R_1 = 100\frac{d}{n}(\Omega) \quad (1)$$

$$R_2 = 65\frac{d}{n}(\Omega) \quad (2)$$

$$L_1 = 0.2\frac{d}{n}(\mu H) \quad (3)$$

$$L_2 = 15\frac{d}{n}(\mu H) \quad (4)$$

$$C = 100\frac{n}{d}(pF) \quad (5)$$

Where, d and n respectively represent the height and number of the parallel ZnO columns in the surge arrester [21].

It is noted that sometimes, the obtained parameters of (1)-(5) in the modeling may lead to the overvoltage across the surge arrester different from the one declared by the manufacturer. In this circumstance, the L2 value can be changed to eliminate this difference. In this paper, the ZnO surge arrester of the Pars Company with the specifications presented in Table 1 is utilized [22].

3.3 Modeling of the distribution feeders

To technically design the distribution feeders, numerous parameters such as passing energy capacity, insulation coordination, mechanical strength, environmental issues and etc., should be seriously taken into consideration. The dielectric strength versus various stresses especially the electrical stresses is so essential in this area.

Table 1 Technical data of the ZnO surge arrester product of the Pars Company

Specifications	Low voltage (kV)	Medium voltage (kV)
Rated voltage (kV)	0.3	25
Continuous operating voltage (kV)	0.240	20
Rated discharge current (A)	10	10
Residual voltage for 10kA @ 8/20 μs (kV)	0.840	73
Column height (m)	0.062	0.37

The insulation system used in the distribution feeders should have sufficient toleration against the lightning overvoltage. In this case, an accurate modeling of such components is mandatory. Among diverse models, the frequency model is the best and most accurate model for the transient state simulation of the distribution feeders.

In this paper, the J-Marti model is employed for the frequency-based modeling of the 20kV distribution feeders [23]. This model uses a fixed conversion matrix for switching from modal domain to the frequency domain. Moreover, this model is generally utilized for the high frequency overhead feeders while it shows non-stable behavior in very low frequency systems. Despite the high accuracy, the J-Marti model has high simulation time and performs slower than the other models. In this paper, the mentioned model is selected for the simulation experiments due to its high accuracy in addition to the possibility of implementation via the FD model (as depicted in Fig. 4) in the EMPT-RV software.

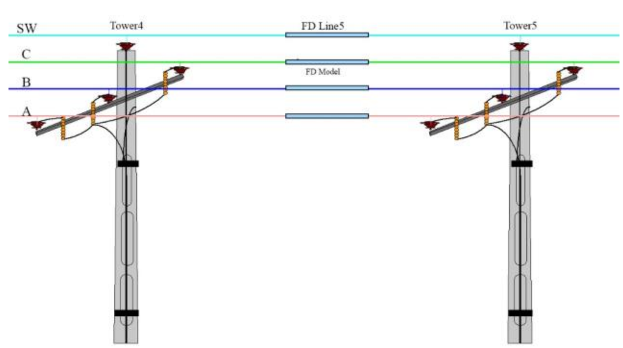

Fig. 4 Schematic of the distribution feeders simulated in the EMTP-RV

3.4 Modeling of the grounding system

The grounding system performance has great influence on the lightning discharge probability. Since the lightning discharge is carried out by the grounding system, an accurate modeling of such system is so important. In this paper, a vertical electrode with 2.5m length, 6mm radius and also relative electrical conductivity of 20 (i.e. ε_r=20) is considered to evaluate the high frequency behavior of the grounding system. The grounding system impedance is modeled for the soil specific resistance of 250Ω.m and two cases of the fixed resistance (R) and frequency dependent impedance.

- **The static resistive model of the grounding system**

In this model, the base impedance is represented by a fixed resistance. The simplest grounding system model for the simulation of the tower footing is the resistive model in which, the grounding electrode is modeled via a fixed resistor. However, the frequency dependence is not seen in this model. In this paper, a 200Ω resistance considered to assess the impact of the fixed grounding resistance, designated to the rocky areas, on the distribution system protection against the lightning overvoltage [24].

- **Frequency -based modeling of the grounding system**

The method of moment (MOM) can effectively solve the electric field integral equations. This method monitors the current flow throughout the grounding system conductors. Moreover, this method is an accurate and numerical technique for solution of the electromagnetic problems. Using this method, the electromagnetic radiations as well as the wave propagation and dispersion can be analyzed with the relatively short run time and low computational burden. Moreover, to solve the electric field integral equations, the MOM method in the frequency domain is generally utilized. For this purpose, the grounding system is estimated by the narrow wires each of them separated to the smaller sections. In order to calculate the longitudinal current distribution, the tangential electric field on each cross section is calculated based on each current sample passing through the conductor axis. Additionally, it can be estimated in the form of a constant value, piecewise sinusoidal or ramp function. Distribution of the current across the grounding conductors and also electric field in the frequency domain can be calculated via solving the electric field integral equation. Then, the voltage increment at the excitation point can be specified through taking the integral of the electric field over the pre-determined path. At the end, the system impedance is computed using the voltage and current values.

In the next step, to attain a certain-order transfer function, the vertical fitting for the frequency response estimation is performed (vertical fitting is a numerical technique for calculation of the frequency responses). This method can directly recognize the state space models from the frequency domain responses of every single input-single output (SISO) system or even multi input-multi output (MIMO) system. The system transfer function can be represented by sum of the partial fractions each of them is modeled as a branch circuit with a specific input value. In this way, a synthesized circuit having the connected parallel branches is constituted. Based on this fact, the soil permittivity and relative conductivity show a frequency-based behavior. Therefore, using a precise soil model can cause the more accurate evaluation of the irradiative electromagnetic fields and also the surge arresters' residual voltage. Since all the calculations in the MOM method are accomplished in the frequency domain, the frequency dependence of the soil parameters are easily calculated [25]. As mentioned, in this paper, a vertical electrode with 2.5m length and 6mm radius is utilized aiming to the frequency-based modeling of the grounding system. Based on the necessity of shield wire application in rocky areas with the high ground resistance, such feature (i.e. high resistance grounding system) is supposed for the simulation experiments of this paper. The frequency-based impedance of the grounding system together with the associated equivalent circuit, considering the specific resistance of 250 Ω.m, is demonstrated in Fig.5.

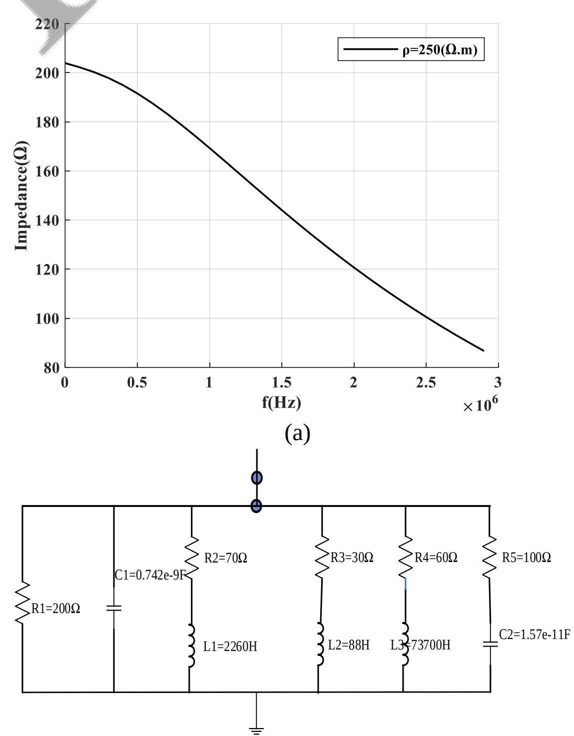

Fig. 5 Frequency-based modeling of the grounding system using MOM **a)** Self-impedances of the vertical rod grounding system **b)** grounding system

3.5 Tower modeling

In this paper, the linear model is considered for the purpose of tower simulation. Generally, the linear model is employed for the tower with less than 30m height. In this model, a losses- free feeder with the surge impedance (as the loading of such feeder) is taken into account for the tower simulation [25]. For a small tower (i.e. less than 30m height), the tower simulation by a simple linear model is physically more appropriate than the transmission line model. Also, the obtained results are closer to the experimental data. To model the small towers, the following equations can be utilized:

$$Z = 60\left[\ln\left(\frac{H}{R}\right) - 1\right] \tag{6}$$

$$R = \frac{r_1 b_2 + r_2 H + r_3 b_1}{2H} \tag{7}$$

The geometrical data of the real-world distribution tower considered for the study purposes of this paper is depicted in Fig. 6.

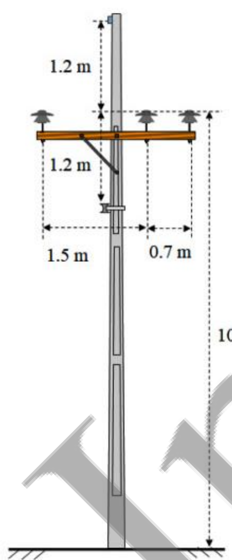

Fig. 6 Geometrical data of the tower used for the simulation experiments [4]

To assess the sundry protective approaches, three case studies for the under-study towers, as shown in Fig. 7, are considered. The case 1 is a concrete three-phase simple tower without the shield wire. The case 2 is the same as the case 1 except the shield wire is added to investigate the lightning overvoltage on the distribution system. In case 3, the lightning rod is considered in addition to the case 2.

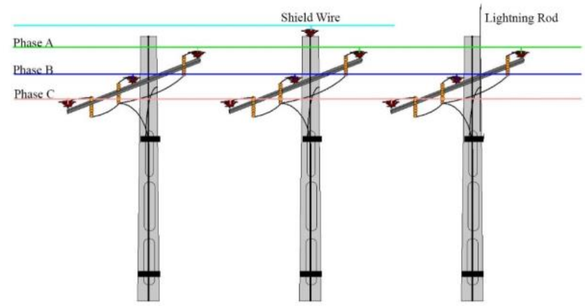

Fig. 7 Towers' schematic used for the simulation study

3.6 Insulator modeling

The insulators are used for isolating the distribution feeders from the towers. Moreover, these devices should withstand the mechanical forces and stresses caused by the abnormal condition occur in the distribution systems. The insulators' failure causes the distribution feeders' outage leading to the techno-economic damage to both distribution utility and the customers [25].

If the lightning overvoltage imposed to the insulator chain exceeds the critical flashover voltage (CFO), the electrical short circuit occurs across this device (i.e. the insulator chain experiences the dielectric breakdown). The simulation of the insulator chain and its parameter calculation depends on the several factors including the specifications of the lighting, operational voltage and the towers' structure. To simulate the insulator chain in the EMTP-RV, the following equation is employed [26]:

$$\int_{t_0}^{t} \left(\left|V_{gap}(t)\right| - V_0\right)^K dt \geq D \tag{8}$$

3.7 Transformer modeling

To investigate the lightning-based overvoltage within the distribution network, it is required to develop a high-frequency model of the distributing transformer. There are several approaches to model the power system transformers, among them, the model presented in (schematically depicted in (Fig. 8)) is employed in this paper. The transformer modeling utilized in this paper is based on the two-port network theory [27] represented by the T equivalent circuit.

In this model, the descriptive parameters are determined through the open circuit tests and based on the two distinct values of the resonance frequency. Moreover, this type of transformer modeling is appropriate for the frequencies in the range of 1kHz to 10MHz and both no-load and full-load conditions.

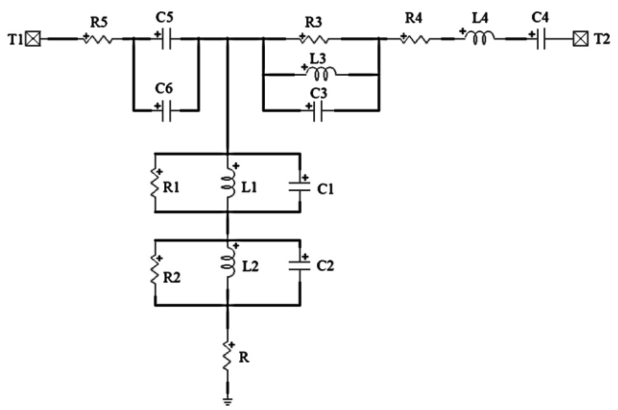

Fig. 8 The transformer model used in this paper

3.8 Load modeling

The overvoltage level in the distribution system highly depends to the load level. At the same context, using more accurate transformer modeling leads to better and more reliable simulation results. In this paper, the RLC model of the loads is utilized [28]. This model can effectively realize the transient high-frequency behavior of the loads compared to the other models [28]. The RLC load model is graphically illustrated in Fig.9 and the corresponding parameters' value is presented in Table 2.

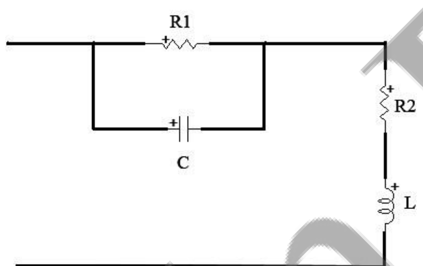

Fig. 9 The RLC Load model

Table 2 The parameters' value pertaining to the RLC load model

R1(Ω)	R2(Ω)	L(μH)	C(nF)
100	2	5	**100**

4 Simulation Results

A comprehensive protection scheme versus the lightning overvoltage is merely possible by the implementation of various protective scenarios on the distribution system. In this paper, diverse scenarios such as the surge arrester, shield wire, lightning rod, etc. is investigated. Hence, in this section, the simulation results obtained by the evaluation of the various protective scenarios in two cases of the direct and indirect LS are presented. The main target here is comparing the frequency-based and resistance model of the grounding system, thus, a 200Ω resistance is considered for representing of both grounding system models in all under-study scenarios.

4.1 Indirect LS

As previously mentioned, the shield wire is used for preventing the direct LS on the distribution feeders. In most cases, the lightning strikes the shield wire and cause the back flashover. By travelling the lightning wave across the feeders, an overvoltage is naturally occurs. In this circumstance, if the dielectric strength of the insulator chain is not sufficient, the dielectric breakdown is inevitable. Therefore, totally, the protection level of the shield wire in the case of the indirect LS is not fully guaranteed and so damage to the insulation level of the distribution system is to some extent probable.

The lightning rod, functionally similar to the shield wire, is another protective device utilized for hedging the distribution system against the direct LS. In practical environment, the major portion of the lightning can be potentially transmitted to the grounding system by using the lightning rod, especially in 20kV distribution system where the towers' distance is low.

A. Scenario I: ***Protection with only shield wire (without the surge arrester)***

To study this scenario, let consider a distribution system with 11 concrete towers, as depicted in Fig. 10, wherein each tower equips with a shield wire and each phase has its own insulator chain. A 30kA lightning wave striking the tower 6 is considered for this scenario.

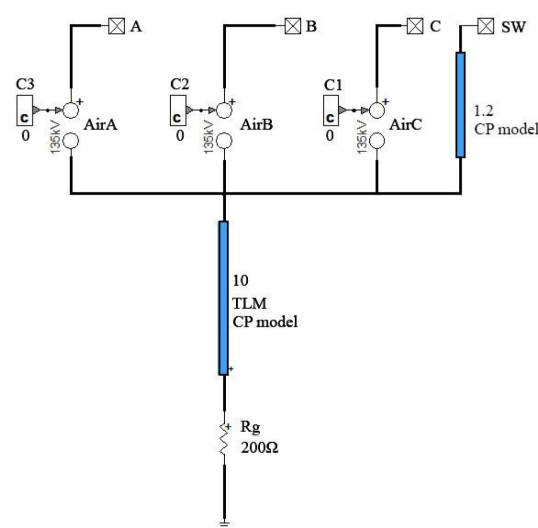

Fig. 10 Simulated tower of the scenario I

After the simulated lightning wave striking the shield wire, the induced voltage across the insulator chain of the tower 6 is evaluated for both frequency-based and resistance model of the grounding system. As depicted in Fig.11, the induced voltage across the insulator chain is 4.5kV less in frequency-based model than the resistance model.

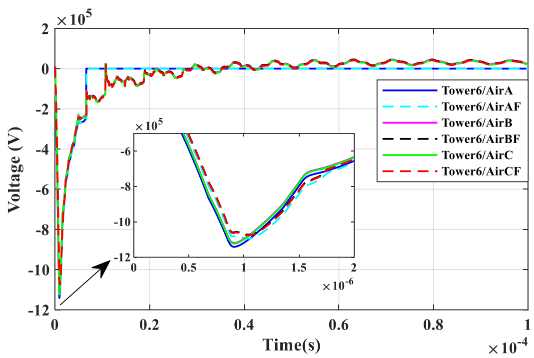

Fig. 11 The induced voltage across the insulator chain pertaining to the tower 6 (scenario I)

In Table 3, the dielectric breakdown occurrence for the insulator chain connected to each phase is presented. As seen, only the insulator chain of the phase A in the tower 6 experiences this challenge for both cases of the frequency-based and resistance model.

Table 3 Dielectric breakdown for the insulator chain connected to the distribution system phases

Tower number	The resistive grounding system			The frequency grounding system		
	A	B	C	A	B	C
Tower 6						
Tower 5,7						
Tower 4,8						
Tower 3,9						
Tower 2,10						
Tower 1,11						

B. Scenario II: ***Protection with both shield wire and surge arrester***

In this scenario, the protective anti-LS performance of both shield wire and surge arrester, as schematically shown in Fig. 12, is assessed. As demonstrated in Fig.13, the induced voltage across the insulator chain is 400V less in the frequency-based model than the resistance model.

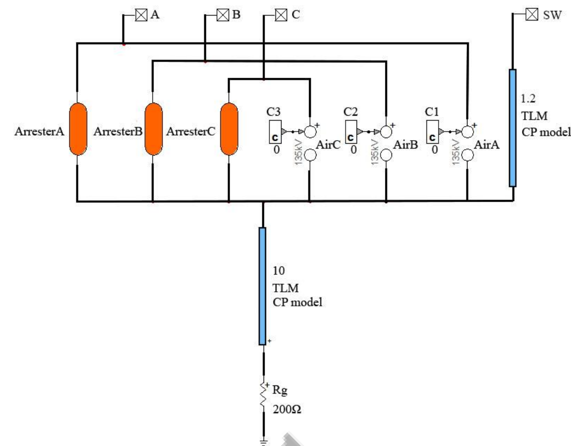

Fig. 12 Simulated tower of the scenario II

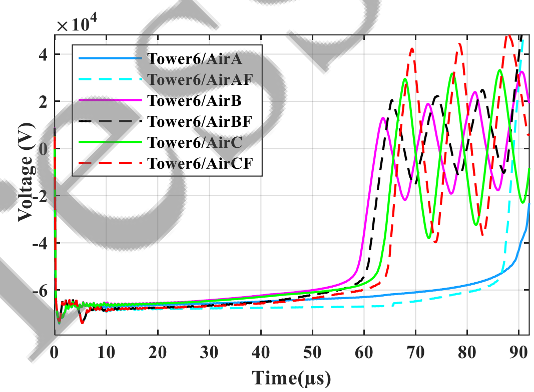

Fig. 13 The induced voltage across the insulator chain pertaining to the tower 6 (scenario II)

It is noted that no dielectric breakdown has occurred in this scenario due to presence of the surge arrester.

C. Scenario III: ***Protection with the lightning rod and surge arrester (without the shield wire)***

In this scenario, as exhibited in Fig. 14, the lightning rod and surge arrester are simultaneously employed and the 30kA lightning current is imposed to the lightning rod of the tower 6. The comparative results, depicted in Fig. 15, justify that the induced voltage across the insulator chain is 200V less in the frequency-based model comparing to the resistance model.

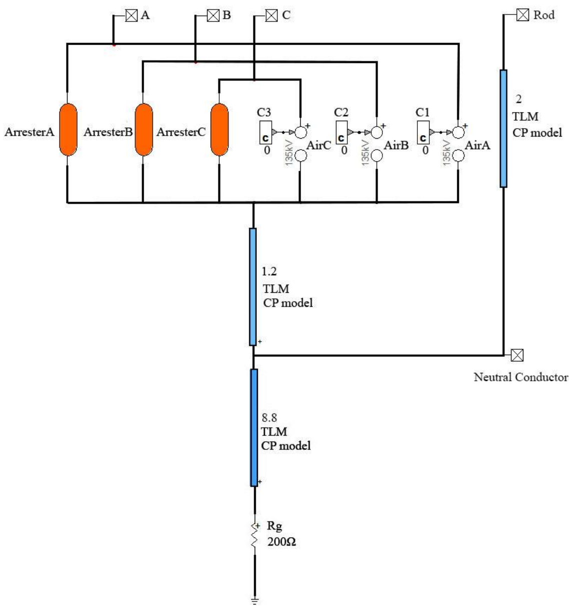

Fig. 14 Simulated tower of the scenario III

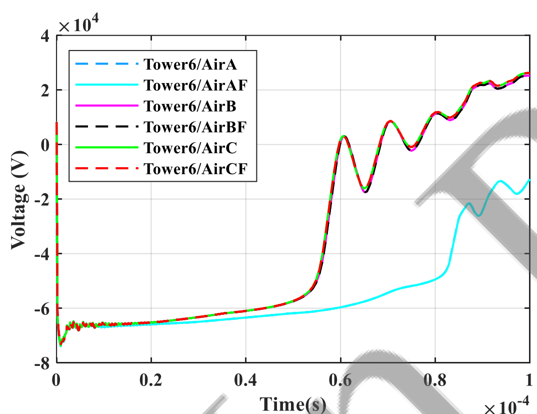

Fig. 15 The induced voltage across the insulator chain pertaining to the tower 6 (Scenario III)

Again, it is observed that any dielectric breakdown has not occurred in this scenario due to presence of the surge arrester.

D. Scenario IV: *Protection with only lightning rod (without the surge arrester and shield wire)*

In this scenario, as depicted in Fig. 16, the protective impact of only lightning rod (i.e. no surge arrester and shield wire is incorporated) is investigated. The simulation results, presented in Fig.17, prove that the induced voltage across the insulator chain is 500V less in the frequency-based model compared to the resistance model.

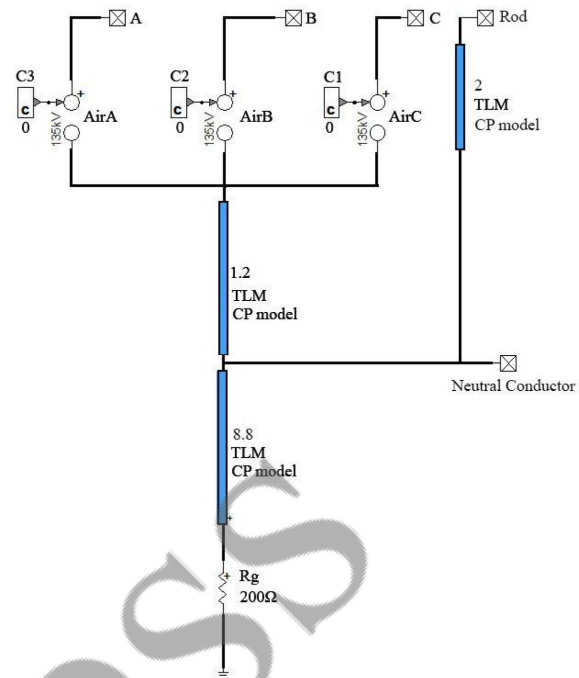

Fig. 16 Simulated tower of the scenario IV

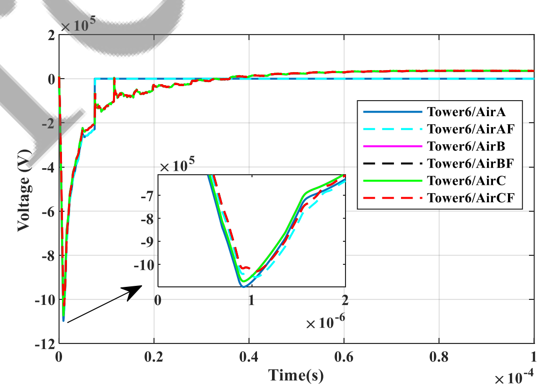

Fig. 17 The induced voltage across the insulator chain pertaining to the tower 6 (scenario IV)

Furthermore, as demonstrated in Table 4, only the insulator chain of the phase A in the tower 6 encounters the dielectric breakdown for both cases of the frequency-based and resistance model.

Table 4 Dielectric breakdown for the insulator chain connected to the distribution system phases (scenario IV)

Tower number	The resistive grounding system			The frequency grounding system		
	A	B	C	A	B	C
Tower 6						
Tower 5,7						
Tower 4,8						
Tower 3,9						
Tower 2,10						
Tower 1,11						

4.2 Direct LS

To study the protective strategies in the case of the direct LS, it is assumed that a 30kA lightning waveform directly strikes one phase and so the resultant overvoltage travels across the system.

E. Scenario V: *Protection with no shield wire and no surge arrester*

In this scenario, the simulation experiment is carried out without any protective devices against the lightning waves. As shown in Fig. 18, in this scenario, neither the surge arrester nor the shield wire is installed at the simulated towers. A 30kA lightning wave striking the phase C of the tower 6 is considered in this case.

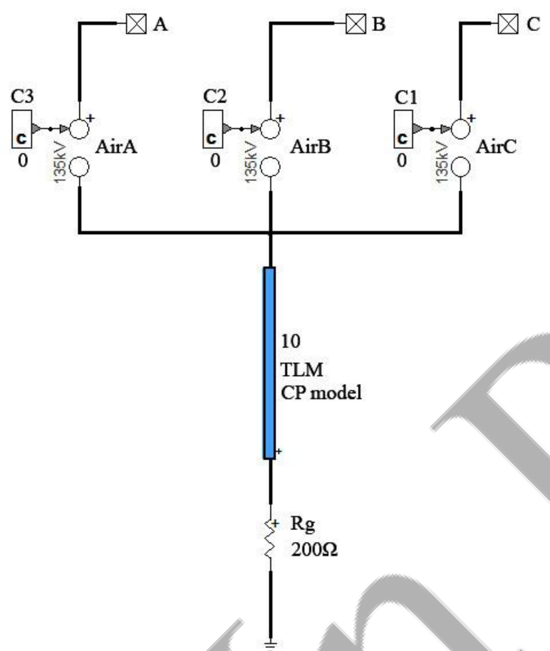

Fig. 18 Simulated tower of the scenario V

The achieved results, graphically illustrated in Fig. 19, verify that the induced voltage across the insulator chain is the same for both cases of frequency-based and resistance model while the dielectric breakdown occurrence is not analogous. As depicted in Table 5, in this scenario, nine dielectric breakdowns for the resistance model and five dielectric breakdowns for the frequency-based model occurs. Because of the direct LS to the phase C of tower 6, the insulator chain connected to phases C of system encounter the dielectric breakdown while the insulator chain connected to phases A and B experiences this challenge due to the back flashover. However, totally speaking, despite no protective device, the superiority of the frequency-based model is evident rather than the resistance model.

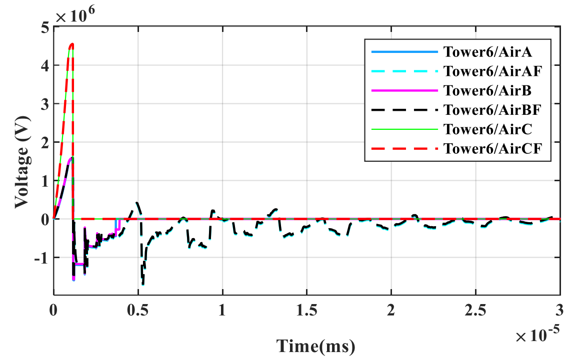

Fig. 19 The induced voltage across the insulator chain pertaining to the tower 6 (scenario V)

Table 5 Dielectric breakdown for the insulator chain connected to the distribution system phases (scenario V)

Tower number	The resistive grounding system			The frequency grounding system		
	A	B	C	A	B	C
Tower 6						
Tower 5,7						
Tower 4,8						
Tower 3,9						
Tower 2,10						
Tower 1,11						

F. Scenario VI*: Protection with the surge arrester and no shield wire*

The surge arrester is considered as the only protective strategy in this case. For the sake of simulation, eleven towers each of them possesses three insulator chains and also three surge arresters, as shown in Fig. 20.

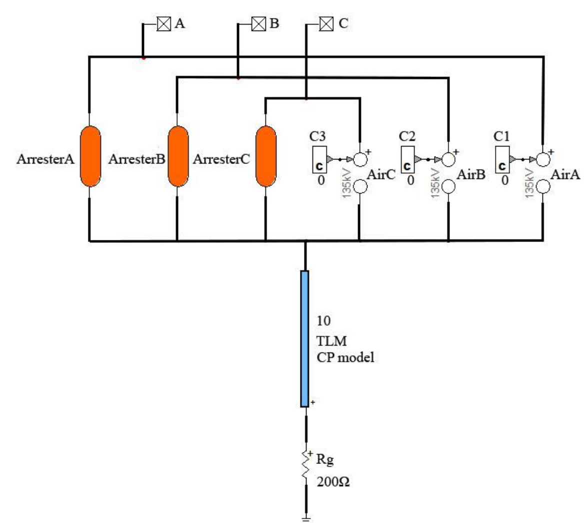

Fig. 20 Simulated tower of the scenario VI

The induced voltage across the insulator chain for both cases of the resistance and frequency-based grounding system is depicted in Fig.21. The grounding system impedance in the frequency-based model is lower than the one in the resistance model. In this way, the lightning current passing through the grounding system and consequently, the induced voltage across the insulator chain is higher for the frequency-based grounding system. The comparative results of the Fig. 21 validate the mentioned issue such that the induced voltage across the insulator chain is 200V more than the corresponding value in the case of the resistance model. Moreover, due to the direct LS, the highest overvoltage is for the phase C. It can be observed that after the direct LS experienced by the phase C and so transmitting the lightning current to the grounding system, the voltage across the insulator chain tends to the normal value of $20/\sqrt{3}$ kV (i.e. the voltage magnitude before the LS occurrence). Furthermore, the dielectric breakdown has not occurred in this scenario due to the presence and performance of the surge arrester.

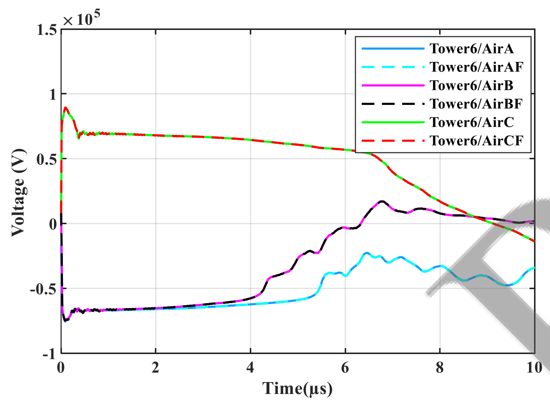

Fig. 21 The induced voltage across the insulator chain pertaining to the tower 6 (scenario VI)

G. Scenario VII*: Protection with both surge arrester and shield wire*

Due to installation angle of the shield wires relative to the distribution phase, the shield wire cannot generally hedge the system against all the probable lightning waves. In this case, the LS over the distribution phases is inevitable. By realizing the LS over the distribution phases (in the presence of shield wire), the protection system encounters the malfunction error and consequently, cause the overvoltage across the insulation system.

The lightning current intensity is a significant factor in the LS evaluation. In this way, if the lightning current is from 3kA to 5kA, the direct LS is so probable due to the protective domain of the shield wire. However, if the mentioned current is 30kA, the direct LS is approximately impossible due to the higher protection radius of the shield wire in this case. Nevertheless, since the latter maybe occurs in the distribution systems, this scenario, i.e. presence of both surge arrester and shield wire, is simulated. In this scenario, a 30kA lightning wave striking the phase C of the tower 6 is considered, as shown in Fig. 22.

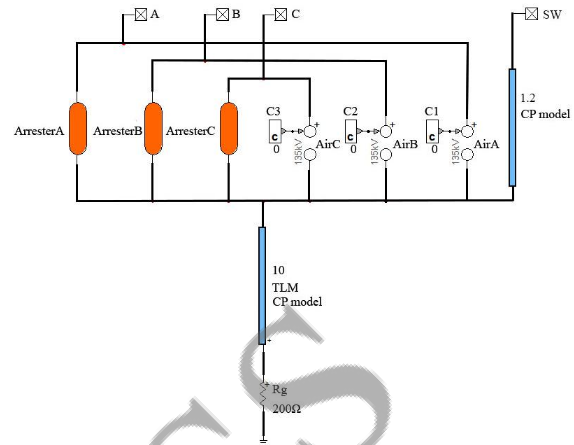

Fig. 22 Simulated tower of the scenario VII

The graphical results of Fig. 23 demonstrate that for the case of the frequency-based model, the induced voltage across the insulator chain is 800V less than the case of resistance model. Additionally, the dielectric breakdown has not happened due to function of the surge arrester.

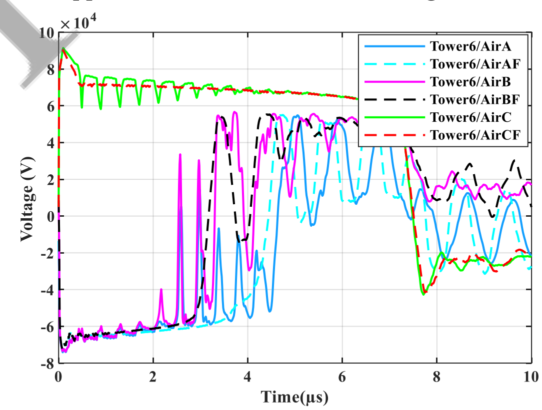

Fig. 23 The induced voltage across the insulator chain pertaining to the tower 6 (scenario VII)

H. Scenario VIII: *Protection with the shield wire and without the surge arrester*

Since the installation of the surge arrester for all phases is not cost-effective, the scenario VII is repeated here without the presence of the surge arrester. In this scenario, the 30kA lightning current, as shown in Fig.24, is imposed to the phase C of the tower 6, similar to the scenario VII.

Comparing the simulation results demonstrated in Fig. 25, it can be seen that the induced voltage across the insulator chain is 100V less in the frequency-based model compared to the resistance model. Meanwhile, the highest overvoltage is associated with the phase C where the direct LS occurs.

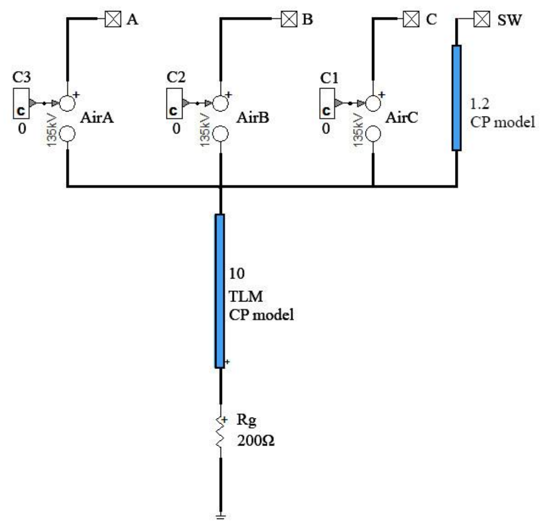

Fig. 24 Simulated tower of the scenario VIII

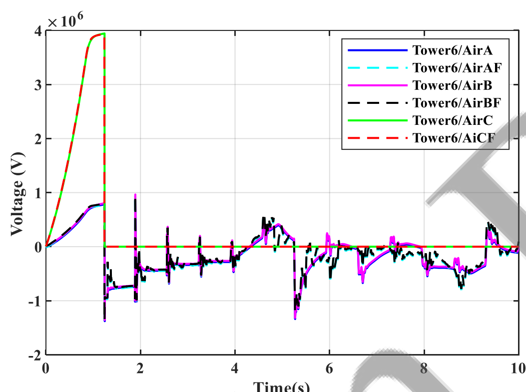

Fig. 25 The induced voltage across the insulator chain pertaining to the tower 6 (scenario VII)

The dielectric breakdown occurs for the insulator chain is presented in Table 6. It is observed that in addition to the phase C of the tower 6, towers before the tower 6 (i.e. towers 4 and 5) and also towers after that (i.e. towers 7 and 8) have experienced the dielectric breakdown.

Table 6 Dielectric breakdown for the insulator chain connected to the distribution system phases (scenario VIII)

Tower number	The resistive grounding system			The frequency grounding system		
	A	B	C	A	B	C
Tower 6						
Tower 5,7						
Tower 4,8						
Tower 3,9						
Tower 2,10						
Tower 1,11						

4.3 Validation

For results validation, The obtained results have a compared to the obtained results in the [4]. The represented results for lightning strikes to the shielding wire and to the phase conductor have been shown in Table 7. As shown in this table, the obtained results and the presented results in [4] are similar approximately which validate the simulation and the obtained results accuracy.

Table 7 The obtained results validation

Strikes	Surge Arrester Numbers	Obtained Results	Result [4]
Strike to phase	One SA	19.8kA	20kA
	Tow SA	17.9kA	18kA
Strike to shielding wire	One SA	9kA	9kA
	Tow SA	4kA	4kA
Strike to Lightning Rod	One SA	10kA	10kA
	Tow SA	4.1kA	4kA

This paper focuses on the investigation of insulator voltage; however, since reference [4] examined Surge arrester current, we also included measurements of this current in our simulation, which can be found in Table.7. For instance, in reference [4], the Surge arrester current resulting from a direct lightning strike on the phase conductor is reported to be 20 kA, while our simulation yielded a value of 19.8 kA (see Fig. 26). Also shown in Fig.27 is the surge arrester current when lightning strikes to shielding wire. The peak current value in the simulation and reference [4] is 9 kA and Fig.28 shows the surge arrester current when lightning strikes to lightning rod, and its value is equal to the reference [4] value.

The results obtained in our simulation are closely aligned with those reported in reference [4]. Overall, the results indicate a good performance of the system under test conditions, with most obtained results reasonably close to expected values.

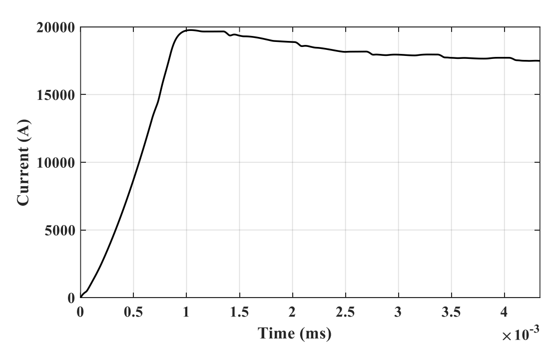

Fig. 26 Surge Arrester current when lightning strikes to phase conductor

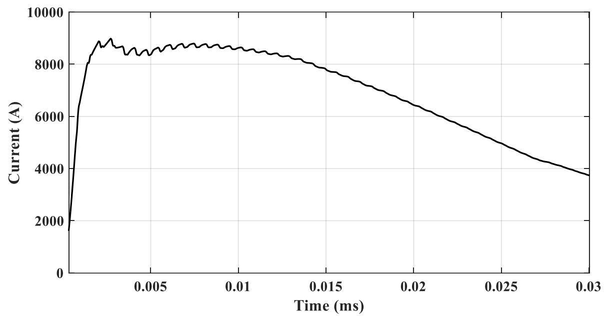

Fig. 27 Surge Arrester current when lightning strikes to shielding wire

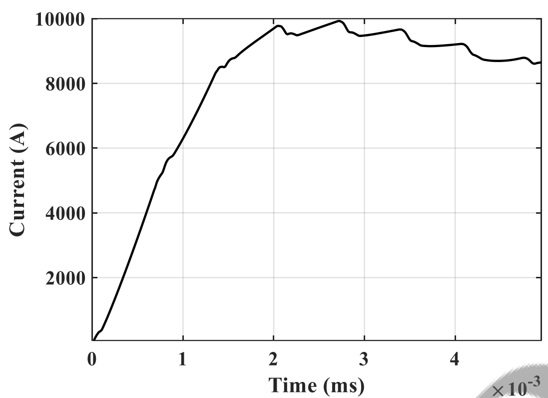

Fig. 28 Surge Arrester current when lightning strikes to Rod

4.4 Impact of the tower footing resistance

To investigate the impact of tower footing resistance, let consider a distribution system with 11 towers each of them equipped with the shield wire and three surge arresters (i.e. each phase has its own surge arrester). In this study, both of the direct and indirect LS are analytically evaluated. In the direct LS, the lightning waves strike the phase C of the tower 6 while in the indirect LS, the lightning waves strike the shield wire of this tower. In order to simulate the tower footing resistance, a simple resistance and a frequency-based resistance is separately considered. It is obvious that the less the tower footing resistance, the easier the transmission of the lightning current to the grounding system. The obtained results for the grounding system once with the simple resistance of 10Ω and 200Ω and once again with 10Ω and 200Ω impedance are respectively presented in Tables 7 and 8. The attained results reveal that the frequency-based model of the grounding system cause better transmission of the lightning to the ground, less back flashover and so less induced overvoltage across the insulator chain. Additionally, in the case of indirect LS (i.e. the LS strikes the shield wire) with the lower grounding system resistance, the induced overvoltage across the system phases is potentially alleviated. This is due to the less frequency-based resistance compared to the simple resistance model of the simulated grounding system.

Moreover, based on the simulation results depicted in the Tables 8 and 9, incrementing the tower footing resistance leads to increase in the induced voltage across the insulator chain (i.e. phase-to-ground voltage). In other words, the lightning current cannot efficiently be absorbed by a high resistance grounding system leading to the overvoltage formation across the insulator chain and also back flashover phenomenon. On the other hand, in the condition of similar resistance, the frequency-based resistance model effectively brings to the less overvoltage across the insulator chain, compared to the simple resistance model.

Table 8 The phase-to-ground voltage for various grounding system in the condition of the indirect LS

The resistance value of (Ω) the ground system	phase-to-ground voltage (kV)	
10	VA=	64.8
	VB=	62.5
	VC=	63.0
200	VA=	74.3
	VB=	73.8
	VC=	73.9
10Ω frequency-based resistance	VA=	64.2
	VB=	61.9
	VC=	62.2
200Ω frequency-based resistance	VA=	73.8
	VB=	73.2
	VC=	73.3

Table 9 The phase-to-ground voltage for various grounding system in the condition of the direct LS

The resistance value of (Ω) the ground system	phase-to-ground voltage(kV)	
10	VA=	63.1
	VB=	62.2
	VC=	90.6
200	VA=	74.1
	VB=	73.4
	VC=	91.5
10Ω frequency-based resistance	VA=	62.9
	VB=	61.8
	VC=	90.1
200Ω frequency-based resistance	VA=	73.2
	VB=	72.7
	VC=	90.6

5 Conclusions

The direct/indirect LS overvoltage is of the main challenges in the distribution systems. Therefore, in this paper, some well-known anti-LS strategies such as the surge arrester, shield wire and lightning rod are analytically analyzed. In the all mentioned protective scenarios, the overvoltage and also the dielectric breakdown across the insulator chain are investigated. In the indirect LS (i.e. the LS on the shield wire or the lightning rod), the obtained results depict that installation of the surge arresters can potentially prevent the dielectric breakdown in the insulator chain. Hence, the best protective approach addressed in this paper is the combinatorial performance of the surge arrester and lightning rod. This is due that in the case of using the lightning rod, the overvoltage across the insulator chain is less than while the shield wire is employed. Moreover, the achieved results illustrate that the surge arrester is the most appropriate scenario for the direct LS protection. It is worthwhile to mention that installation of the surge arrester at all low distance towers of the 20kV distribution systems are not economic and so simultaneous application of the lightning rod and shield wire is more cost-effective. Additionally, the attained simulation results for the scenario V shows that the worst-case dielectric breakdown in the insulator chain occurs while no protective device is used. However, the frequency-based modeling of the grounding system causes only one dielectric breakdown. Thus, it is concluded that the frequency-based modeling of the grounding system can potentially alleviate the overvoltage across the insulator chain and in some cases, prevent the back flashover phenomenon. For lightning strikes to the phase conductor, with and without surge arrester installation the overvoltage has been decreased 55.9 %. In addition, with surge arrester installing, the overvoltage amplitude for frequency grounding system has been decreased 0.5% compared to the static resistor. For lightning strikes to the shielding wire, with and without surge arrester installation the overvoltage has been decreased 34.9%. In addition, with surge arrester installing, the overvoltage amplitude for frequency grounding system has been decreased 0.54 % compared to the static resistor. Additionally, the use of a frequency grounding system, due to its accurate modeling, yields more precise results compared to a static resistor approach. The MOM simulation reveals a 50% reduction in breakdown voltage under the worst-case scenario, and overall overvoltage experiences a 2% decrease.

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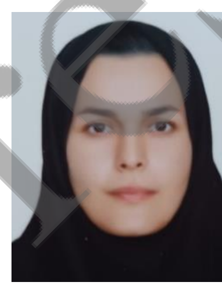

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