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Frequency Grounding System Effect on the EGLAs Placement in a 400 kV Transmission Line

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Abstract: In this paper, the performance of the EGLA (Externally Gaped Line Arresters) and its impact on the back flashover rate of a 400 kV transmission line have been investigated. The frequency behavior of the grounding system and soil resistivity has been modeled. To analyze the EGLA performance in relation to the grounding system's frequency behavior, a rod-shaped grounding system model has been implemented. By placing the EGLA at different phases of the transmission line, the best scenario has been identified to minimize back-flashover occurrences. Furthermore, the performance of the frequency grounding system to that of the nonlinear grounding system has been compared. The results clearly indicate that using a nonlinear grounding system leads to higher back flashover rates compared to the frequency grounding system. Additionally, the EGLA absorbs less energy when connected to a nonlinear resistor compared to the frequency grounding system. It can be concluded that modeling the grounding system's frequency behavior using the frequency grounding model provides more accurate results, especially in investigations related to power grid insulation coordination.

Keywords: Externally Gapped Line Arrester, Frequency Grounding System, Lightning Performance, Transmission Line.

1 Introduction

EXTTERNAL events such as lightning strikes, along with internal factors like faults, switching operations, ferro-resonance, and load rejection, either individually or in combination, can lead to overvoltage in power systems. Lightning strikes particularly pose a significant risk to transmission and distribution lines, often resulting in power outages, insulation breakdowns, and equipment failures [1], [2], [3]. These surges can affect shield wires, transmission line towers, and the surrounding ground, inducing voltage and potentially causing back-flashover (BF) across insulator strings, leading to faults. Moreover, direct strikes to phase conductors can result in shielding failure. The installation of shielding conductors along transmission lines can mitigate the impact of such events. Lightning's impact on power systems can be broadly categorized as direct or indirect [4], [5].

Various studies have been conducted to investigate the effects of lightning on transmission lines and substations. These studies have led to the development reducing tower footing resistance, installing downstream shield wires, and utilizing surge arresters (SAs). Selecting the optimal technique, considering both technical and economic aspects, for enhancing the performance of transmission lines against lightning strikes requires further exploration. For instance, reducing tower footing resistance in mountainous regions is often costly and challenging. Therefore, using surge arresters, shielding wires, and downstream shield wires can be practical solutions to improve the reliability of transmission lines [6], [7].

Installing surge arresters in transmission lines is a suitable solution for reducing insulation failures,

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lightning-related outages, and improving network reliability. However, the performance of surge arresters is influenced by various factors, including installation conditions, lightning characteristics, and ground resistance. There are two types of surge arresters: those with an external air gap (EGLA) and those without. Non-gapped line arresters, which feature high energy absorption capability and switching impulse withstand ability, are recommended for system voltages above 245kV due to their reliable protection. EGLAs, consisting of zinc oxide varistors and an external air gap, are widely used because they are environmentally friendly, have no deterioration issues, facilitate successful reclosing processes, and offer superior protective performance with lower residual voltage. However, EGLAs have limitations in protecting against switching transient overvoltage [8], [9], [10]. This paper specifically focuses on EGLA surge arresters. As the majority of lightning strikes hit the tower or shielding wire [11], this work primarily investigates back-flashover phenomena.

To economically install surge arresters, flashover phenomena have been studied on a 132 kV double-circuit line using EMTP software. The effect of grounding resistance, lightning characteristics, and system voltage have been examined to determine the appropriate surge arrester configuration for reducing back-flashover. A model has been developed using ATP-EMTP software to evaluate the performance of overhead lines and substations, considering different surge arrester currents and footing resistances for back-flashover in a 220 kV transmission line. It is concluded that proper calculation of surge arrester energy absorption capacity is essential for designing an effective protective system [12], [13].

While there have been many studies on surge arresters' performance against lightning, EGLAs' performance has not been comprehensively investigated. The placement of EGLAs in a 220 kV double-circuit transmission line has been examined [5], specifically focusing on their impact on back-flashover performance. The results show that increasing the number of EGLAs does not significantly reduce their discharge current. However, when the number of EGLAs in a transmission line increases, their discharge current should be reduced. It is not reasonable to install EGLAs on all phases for lightning protection in transmission lines. The theoretical investigation of EGLA placement in a transmission line with downstream shield wire [14] has explored the additional effects of shielding wires by solving Maxwell's equations. The results show that an additional ground wire can reduce induced voltage and current on insulators and can impact transient traveling wave impedance. Previous papers [2], [5], [10] have described the advantages of EGLAs but have not determined the better type of EGLA for practical use. The impact of the best type of EGLA and EGLA placement in transmission lines has been evaluated [6], concluding that for improved lightning performance, grounded wires should be installed below the phase wires. However, this consideration has not been made for double-circuit transmission lines with a multi-story tower model, which has been addressed in [8]. This study explores the consequences of installing various types of EGLAs, along with downstream shield wire, on the occurrence of back-flashover. The performance of four types of EGLAs has been investigated in [8], revealing that EGLAs with an active part series and externally fixed air gap performed better than the others. Moreover, installing downstream shield wire has a significant impact on reducing back-flashover.

The performance of EGLAs and their placement effects on the back-flashover rate have been examined in these papers. However, the grounding system has been modeled using a static resistor or nonlinear resistor with ionization effects, without considering the frequency behavior of the grounding system and soil resistivity. To obtain more accurate results, it is necessary to evaluate the frequency behavior of the grounding system's effect on EGLA performance in transmission lines. This paper models a rod-shaped grounding system to investigate the frequency behavior of the grounding system's effect on EGLA performance, taking into account the frequency-dependent behavior of soil conductivity and relative permittivity. The effect of the best type of EGLA has been investigated to study the EGLA placement in the performance of transmission lines with downstream shield wire. By EGLA placing in different phases of a transmission line, the best scenario for less back-flashover occurrence has been elected.

2 System Modelling

Computer analysis is a valuable tool for studying the performance of equipment, as long as an accurate model of the component is utilized. In order to examine the performance of EGLAs and the transient behavior of the system under investigation, the following equipment models have been utilized:

2.1 Transmission Line and Tower

The analysis of the 400 kV double-circuit transmission line involves representing it with six spans, comprising seven towers in total, each span having a length of 300 meters. This transmission line configuration includes two shielding wires and two downstream shield wires. To ensure precise modeling of the transmission line, the FD model within the EMTP-RV software has been utilized. This model accounts for distributed and frequency-dependent line parameters, incorporating factors such as line resistance and inductance. These parameters are determined by considering phenomena like skin effect and ground return at various frequencies. For detailed information regarding this model [15].

For tower heights exceeding 40 meters, a multistory model, as shown in Fig. 1, has been utilized to simulate the tower instead of a lumped model [5]. The parameter values have been determined based on the equations provided in [16].

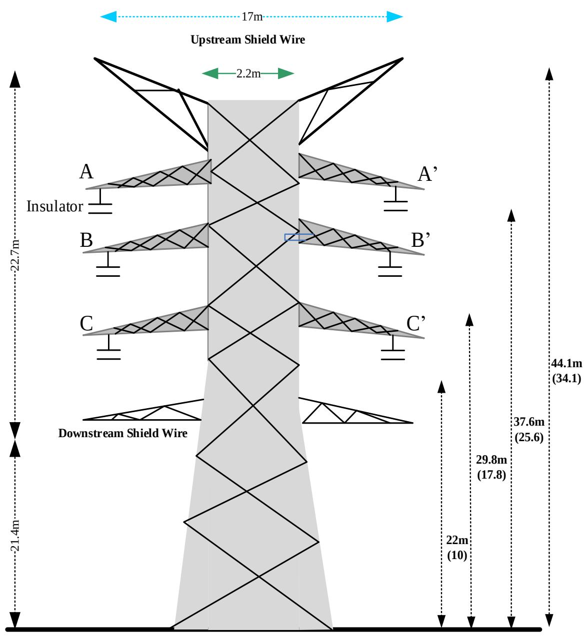

Fig. 1 A schematic diagram of a 400 kV transmission tower

2.2 Lightning Stroke Model

The lightning stroke has been represented in the analysis as a current source running in parallel with a resistor (1 kΩ). To simulate negative downward discharge strikes on the shield wire, a CIGRE model has been employed. The parameters for the front time and tail time of the current have been chosen as 3 µs and 77.5 µs, respectively [8].

2.3 Insulator string model

To model the insulator string, it can be visualized as a capacitor connected in parallel with a voltage-controlled switch. During normal conditions, the insulator string has been implemented as the capacitor and during the flashover, the voltage-controlled switch will be closed. In this study, the integration method illustrated in Eq.(1) has been utilized to model the insulator string, as detailed in [17], [18].

$$DE = \int_{t_0}^{t} (V(t) - V_0)^k dt \qquad (1)$$

where DE (kV^k. µs) is the disruptive effect of the applied impulse voltage, V_0 (kV) is the necessary lowest voltage, t_0 (µs) is the time that the $V(t)$ go above than V_0, k is a constant factor. In this method, breakdown takes place once the DE becomes identical to or greater than the critical disruptive effect DE^*.

2.4 Grounding System Model

Nonlinear Grounding System

One of the important factors in the insulator flashover events is grounding system performance, so the grounding system model during lightning strikes discharging is very essential. Nonlinear resistance with a soil ionization effect is a typical grounding system model which used to simulate grounding system behavior. In this model, the tower footing impedance has been displayed by a nonlinear resistance where the soil ionization changes with the exchange in flowing current from the tower footing [19].

Frequency Impedance Model

The Method of Moments (MoM) is a highly effective approach utilized for solving electric field integral equations, with a primary focus on determining the current distribution along grounding system electrodes. The solution to these equations is obtained in the frequency domain using the moment's method. The grounding system is considered to be comprised of thin wires that are divided into smaller segments. To calculate the longitudinal current distribution, the tangential electric field is computed for each segment of the grounding system.

The electric field integral equation is then applied to determine the current distribution along the grounding electrodes and the electric field throughout the solution domain. The voltage rise at the excitation port is obtained by integrating the electric field along a predefined path. Finally, the system impedance is determined based on the voltage and current amplitudes. To estimate the frequency response, the technique of vector fitting is employed. Vector fitting is a numerical method utilized for fitting or calculating frequency domain responses. It enables the calculation of state-space models directly from the frequency domain responses of single or multiple input-output systems.

The system transfer function is expressed as the sum of partial fractions, where each part is represented as a branch circuit with a specific admittance. The synthesis of the circuit is then completed by connecting these branches in parallel, as referenced in sources [20], [21], [22], [23], [24].

In this study, a rod-shaped electrode, as shown in Fig. 2, is considered to investigate the frequency behavior of the grounding system in terms of EGLA and transmission line performances. The electrode has a length of 6 m and a radius of 8 mm. As an example, Fig. 3 presents the synthesized circuit of the grounding impedance and its amplitude for a soil with a resistivity of 500 Ω-m. As depicted in Fig. 3, the amplitude of the footing resistance at low current and low frequency is determined to be 92.34 Ω for the rod-shaped grounding system described in the paper.

Fig. 2 Rod-shape Grounding system model

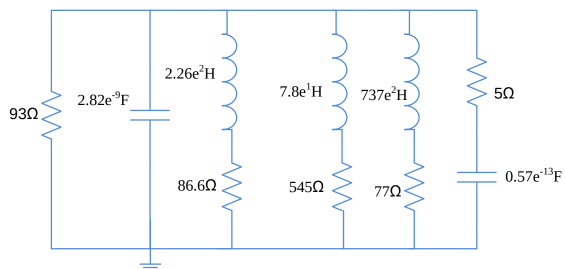

Fig. 3 Rod grounding system model for ρ= 500 Ω-m

2.5 EGLA Modeling

The EGLA is comprised of a non-linear metal-oxide resistor and an air gap. A field test experiment described in [25] was conducted to validate the performance of the 400 kV EGLA test setup, complying with the requirements specified in IEC 60099-8. The test results, which examined various air gaps, evaluated the response to switching wet and lightning-dry impulse voltages. The type tests affirmed the satisfactory functionality of the EGLA [25].

To model the active part of the EGLA, which includes zinc oxide varistors, the IEEE frequency-dependent model [26] was utilized. Fig. 4 illustrates the active part, which is defined by five parameters (R0, L0, L1, R1, and C). In this model, the inductance corresponding to magnetic fields surrounding the surge arrester is represented by L0. To ensure numerical stability during the implementation of the IEEE model in a computer program, R0 is employed. The filter between the two non-linear resistances (A0 and A1) is characterized by the inductance L1 and the resistance R1.

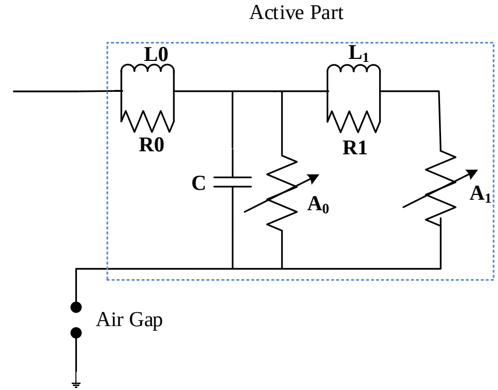

Fig. 4 EGLA model including IEEE model series with air gap

The capacitance between the terminals of the surge arrester is denoted by C in the model. During slow front surge waves, the filter impedance (L1 in parallel with R1) becomes low, causing A0 and A1 to be in parallel. Conversely, during fast front waves, the filter impedance is high, enabling the lightning current to pass through the non-linear resistance A0. [26] provides more details on the calculation of the parameters for the IEEE model. Regulating the gap distance is crucial for this type of arrester. The gap should be large enough to withstand transient overvoltages and yet small enough to spark over before the insulator flashes over. The gap distance can be determined by averaging the minimum and maximum externally recorded gaps of the surge arrester [27]. The minimum acceptable gap setting of an EGLA is determined by three factors: the system voltage, expected temporary overvoltage levels (TOV), and a safety factor (K). Because there is no current flow through the arrester prior to flashover of the gap, the arrester does not influence the gap flashover voltage. The minimum AC Power frequency voltage that EGLA gap will flashover is:

$$V = \frac{V_{sys}}{1.73} \times TOV \times SF_1 \quad (kV_{rms}) \qquad (2)$$

Where V is minimum power frequency flashover voltage, V_{sys} is system voltage and TOV and SF1 are 1.4 and 1.2, respectively.

If the gap spacing has been installed below the minimum level, the flashover risk increases during a temporary overvoltage event and leading to arrester damage or failure. If the gap has been installed with its separation above the maximum recommended level, it may cause the insulator flashover before the gap sparks over. Equation (3) shows the EGLA gap calculation. In this case, the averaged gap distance is 1675 mm [8]. Referring to the IEC 60060-1 standard, the air gap's equivalent sustainable voltage is specified as 896 kV.

$$d_{max} = \frac{V_{CFO} \times 0.85}{E_0}$$

$$d_{min} = 39.37 \left[\frac{e^{\frac{V}{750}} - 1}{0.55} \right]^{0.833} \quad \text{(Inches)} \tag{3}$$

3 Simulation Results

The 400 kV transmission line, as shown in Fig. 1, has been simulated to study the grounding frequency system effect on the EGLA performance. The towers have been simulated by the multistory model and the insulator strings have been modeled based on the integration method. The IEEE model has been used to model EGLA active part and its series external gap has been modelled based on the integration method. The following section presents the EGLA performance for nonlinear and frequency grounding system. The influence of grounding system frequency impedance on the EGLA performance so as to insulator back flashover reduction has been performed. It is supposed that lightning surge strikes to the top of the middle tower in the studied transmission line. In addition, the EGLA absorbed energy and discharge current have been studied.

3.1 EGLA Simulated Model and its Residual Voltage

Parameters of the studied EGLA have been shown in Table 1 [28]. As mentioned in section 2.5, the EGLA active part simulation has been done based on IEEE model in EMTP-RV software. To simulate the air gap, the integration method's mentioned in section 2.3 has been used. It is obvious that the simulated model is able to simulate EGLA residual voltage in accordance with the reported residual voltage by the manufacturer.

Table 1 EGLA Parameters

System voltage (kV)	420
EGLA rated voltage (kV)	360
Nominal discharge current (kA), 2/20µs	15
Residual voltage (kV) at 15 kA, 2/20µs	918
Max. Discharge Current 2/20µs (kA)	40
Creepage distance (mm)	6000

3.2 EGLA Placement Effect on the Insulator Back Flashover

In this section, the impact of the grounding system on the performance of EGLA and the optimal placement of EGLA have been examined. Initially, the influence of different types of grounding systems on EGLA performance and insulator overvoltage was investigated. The scenario assumed the installation of EGLAs on the upper phases of all towers, with a lightning strike occurring on the shielding wire of the central tower (tower 4). Fig.5 and Fig.6 illustrate the EGLA following current and residual voltage, respectively, for the EGLA installed on the central tower's phase A. The lightning parameters used in this case were 300 kA 3/77.5 µs, and the soil resistivity was set at 500 Ω.m.

Fig. 5 shows that the EGLA current differs for the nonlinear grounding system and the frequency grounding system models, with more current passing through the EGLA in the nonlinear grounding system model. In Fig. 6, it can be observed that the peak residual voltage for the nonlinear grounding system is higher compared to the frequency grounding system. Hence, for a thorough investigation of EGLA and transmission line performances, accurate modeling of the grounding system is essential. While the suggested results in [8] regarding EGLA placement were obtained using the nonlinear grounding system, precise modeling of the grounding system is necessary to achieve more accurate and reliable results.

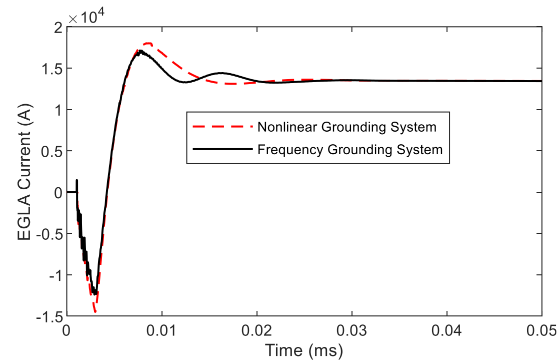

Fig. 5 The EGLA following current installed on the central tower (phase A)

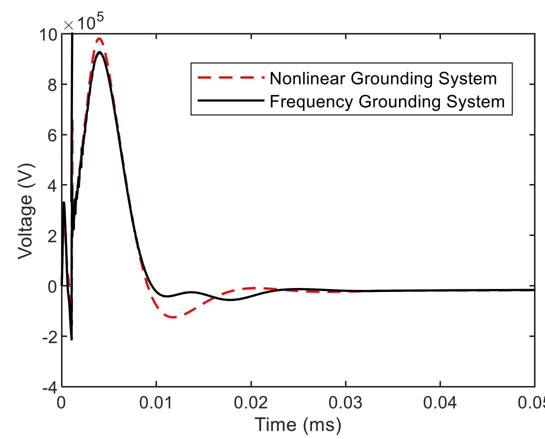

Fig. 6 The EGLA residual voltage installed on the central tower (phase A)

This study verifies the efficacy of insulation coordination between EGLAs and insulators, drawing from the insights provided in reference [27]. Moreover, Fig. 7 illustrates various scenarios of EGLA placement on transmission towers, with the violet color indicating the position of EGLAs on each tower. Flashover occurrences in EGLAs or insulators are denoted by the symbol X, while situations without flashovers are represented by an empty mark in the table.

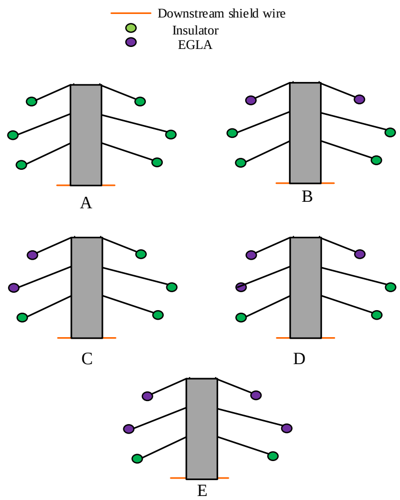

Fig. 7 Various situations of EGLA placement at the towers

Probability calculations are based on these flashover occurrences, where back-flashover occurs when the voltage difference surpasses a predefined value for an insulator string. Breakdowns in insulators or EGLA performance are deduced from lightning flashover charts, with X symbolizing the nonlinear grounding system and Y representing the frequency grounding system. Results for both grounding systems are detailed in Tables 2-6.

Table 2 Back-flashover probability due to strike to the shield wire (Case A)

Tower Number		Lightning Current 120	150	180	210	240	270	300
Tower 1 Tower 7	A	X	X	X	XY	XY	XY	XY
	B						X	X Y
	C						XY	XY
	A′		X	X	XY	XY	XY	XY
	B′						X Y	X Y
	C′					X	XY	XY
Tower 2 Tower 6	A			X	XY	XY	XY	X Y
	B					X	XY	XY
	C						XY	XY
	A′			X	X	XY	XY	X Y
	B′				X	XY	XY	XY
	C′						X	XY
Tower 3 Tower 5	A						X	X
	B				X	X Y	X Y	X Y
	C						XY	XY
	A′					X	X	X
	B′				X Y	X Y	X Y	X Y
	C′						XY	XY
Tower 4	A			X	X Y	X Y	X Y	X Y
	B		X	X Y	X Y	X Y	X Y	X Y
	C						X	XY
	A′		X	X	X Y	X Y	X Y	X Y
	B′			X	X	X Y	X Y	X Y
	C′						X	XY

Table 3 Back-flashover probability due to strike to the shield wire (Case B)

Tower Number		Lightning Current 120	150	180	210	240	270	300
Tower 1 Tower 7	A		X	X Y	X Y	X Y	X Y	X Y
	B							
	C							
	A′		X Y	X Y	X Y	X Y	X Y	X Y
	B′							
	C′							
Tower 2 Tower 6	A		X Y	X Y	X Y	X Y	X Y	X Y
	B							
	C							
	A′		X	X	X	X Y	X Y	X Y
	B′							
	C′							
Tower 3 Tower 5	A			X Y	XY	X Y	X Y	X Y
	B		X	X Y	X Y	X Y	X Y	X Y
	C							
	A′		X Y	X Y	X Y	X Y	X Y	X Y
	B′		X	X	X Y	X Y	X Y	X Y
	C′							
Tower 4	A							X Y
	B		X	X	X Y	X Y	X Y	X Y
	C							
	A′							X Y
	B′		X	X	X Y	X Y	X Y	X Y
	C′							

Table 4 Back-flashover probability due to strike to the shield wire (Case C)

Tower Number		Lightning Current 120	150	180	210	240	270	300
Tower 1 Tower 7	A	X	X	X Y	X Y	X Y	X Y	X Y
	B	X	X Y	X Y	X Y	X Y	X Y	X Y
	C							
	A′							
	B′							
	C′							
Tower 2 Tower 6	A	X	X Y	X Y	X Y	X Y	X Y	X Y
	B	X	X	X Y	X Y	X Y	X Y	X Y
	C							
	A′					X Y	X Y	X Y
	B′							
	C′							
Tower 3 Tower 5	A	X	X Y	X Y	X Y	X Y	X Y	X Y
	B	X	X	X	X	X	X	XY
	C							
	A′							Y
	B′				X	XY	X Y	X Y
	C′							
Tower 4	A							
	B					X	X Y	X Y
	C							
	A′			X	X	X Y	X Y	X Y
	B′		X	X	X Y	X Y	X Y	X Y
	C′							

According to the presented results, the use of the nonlinear grounding system leads to higher rates of back flashovers compared to the frequency grounding system. Modeling the grounding system with frequency behavior, which is more accurately accomplished using the frequency grounding system, leads to more precise outcomes in investigating insulation coordination in power grids.

Table 5 Back-flashover probability due to strike to the shield wire (Case D)

Tower Number		Lightning Current 120	150	180	210	240	270	300
	A				X Y	X Y	X Y	X Y
	B				X Y	X Y	X Y	X Y
Tower 1	C							
	A’							
Tower 7	B’			X	X Y	X Y	X Y	X Y
	C’							
	A		X Y	X Y	X Y	X Y	X Y	X Y
	B				X Y	X Y	X Y	X Y
Tower 2	C							
	A’			X	XY	XY	XY	XY
Tower 6	B’						X	XY
	C’							
	A		X	X Y	X Y	X Y	X Y	X Y
	B			X	X Y	X Y	X Y	X Y
Tower 3	C							
	A’			X	X Y	X Y	X Y	X Y
Tower 5	B’			X	X	X Y	X Y	X Y
	C’							
	A							
	B			X	XY	XY	XY	XY
Tower 4	C							
	A’							
	B’			X Y	X Y	X Y	X Y	X Y
	C’			X Y	X Y	X Y	X Y	X Y

Therefore, it is recommended to model the frequency grounding system for assessing service unavailability of transmission lines and determining surge arrester placement to obtain more accurate results. The proposed results indicate that when a downstream shield wire and EGLA are utilized, no back-flashover occurs on lower phases, avoiding double-circuit outages. Consequently, EGLA installation on lower phases is unnecessary when a downstream shield wire is present, and EGLAs are installed on other phases.

Tables 3-4 present results illustrating that using two EGLAs in the top phases of a double circuit transmission line (Case B) can decrease the flashover rate, while installing EGLAs on the upper and middle phases of each circuit (Case C) can prevent double-circuit faults.

Results for the installation of three EGLAs are shown in Table 5. According to the presented findings, using three EGLAs in the upper and middle phases can reduce back flashover occurrences, and there are no back-flashovers on the lower phases, eliminating the need for EGLA installation on those phases. Table 6 demonstrates EGLA placement in all upper and middle phases except the lower phases, as shown in case G. Due to the low overvoltage in the lower phases, EGLA placement in those phases is not essential. Additionally, using four EGLAs yields fewer back flashovers, but it is a costly option compared to other scenarios. The represented results in Tables 2–3 illustrate that two EGLAs utilization in the top phases of a double circuit transmission line (Case B) can decline the flashover rate, but the EGLAs installation on the upper and middle phases of each circuit (Case C) can prevent to double-circuit fault.

Table 6 Back-flashover probability due to strike to the shield wire (Case E)

Tower Number		Lightning Current 120	150	180	210	240	270	300
	A		XY	X Y	X Y	X Y	X Y	X Y
	B		X	X Y	X Y	X Y	X Y	X Y
Tower 1	C							
	A’		X Y	X Y	X Y	X Y	X Y	X Y
Tower 7	B’		X	X Y	X Y	XY	X Y	X Y
	C’							
	A		X	X	X Y	X Y	X Y	X Y
	B			X Y	X Y	X Y	X Y	X Y
Tower 2	C							
	A’		X	X Y	X Y	X Y	X Y	X Y
Tower 6	B’			X Y	X Y	X Y	XY	X Y
	C’							
	A	X	X Y	XY	X Y	X Y	X Y	X Y
	B							
Tower 3	C							
	A’	X	X Y	X Y	X Y	X Y	X Y	X Y
Tower 5	B’					X	XY	XY
	C’							
	A						X Y	X Y
	B			X Y	X Y	X Y	X Y	X Y
Tower 4	C							
	A’							X Y
	B’			X Y	X Y	X Y	X Y	X Y
	C’							

The back flashover number of EGLA and also insulator for nonlinear and frequency grounding systems have been represented in Fig. 8 and Fig. 9 respectively. As shown in represented results, the appropriate installation location of EGLA including downstream shield wire is able to improve the transmission line performance against lightning for both nonlinear and frequency grounding systems. In addition, in Case G, the utilization of downstream shield wire and four EGLAs declines the back-flashover probability near zero for the nonlinear grounding system and to zero for the frequency grounding system. Double-circuit fault elimination was another essential income of EGLA installation by means of more than two EGLAs in the transmission line.

Comparing Fig. 8 to Fig. 9, considering the frequency grounding system leads to a lower number of flashovers compared to the nonlinear resistor. A nonlinear grounding system causes more return current to pass through the insulator or EGLA and so leading to more flashover probability. For precise investigation of grounding system it is necessary to model grounding system behavior correctly, so more accurate and reliable results can be calculated.

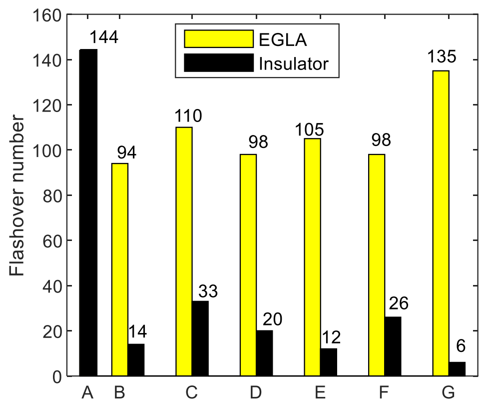

Fig. 8 The back flashover number of EGLA and also insulator for nonlinear grounding systems

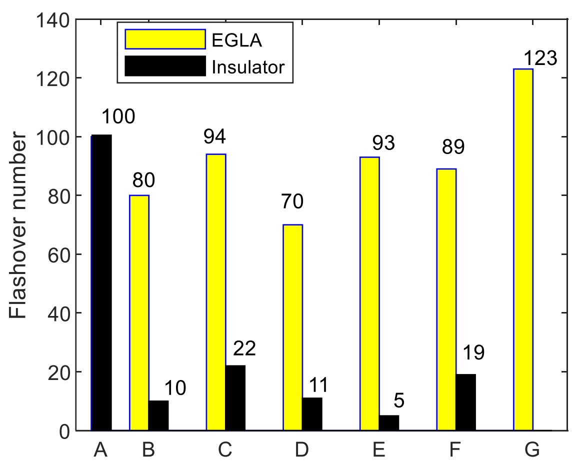

Fig. 9 The back flashover number of EGLA and also insulator for frequency grounding systems

3.3 EGLA Absorbed Energy

The energy absorption capability refers to the amount of energy that a surge arrester can absorb before it fails. According to statistics, approximately 80% of surge arrester failures are caused by lightning strikes, which can result in malfunctions during operation. This is primarily due to the occurrence of overvoltage with high amplitudes of stored energy [8]. To calculate the absorbed energy of a surge arrester, the following equation, as provided in [29], is utilized:

$$E = \int_{t_0}^{t} V_s(t).I_s(t).dt \quad (4)$$

where E is the absorbed energy, V_s is the surge arrester voltage, I_s is surge arrester discharge current, and t_0 is the time that lightning appears at surge arrester terminal.

The EGLA absorbed energy for nonlinear and frequency grounding system has been shown in Fig. 10 for lightning stroke to upper shielding wire. The lightning strike has been hit to the middle tower shielding wire. As shown in Fig. 10, the EGLA absorbed energy is increased according to the lightning current increment. For both considered grounding system, case C has the lowest absorbed energy amount compared to other cases, and the most absorbed energy is related to case G. As shown in Fig. 10, frequency grounding system effect on the EGLAs is obvious, and the absorbed energy for frequency grounding system is higher than the nonlinear grounding system.

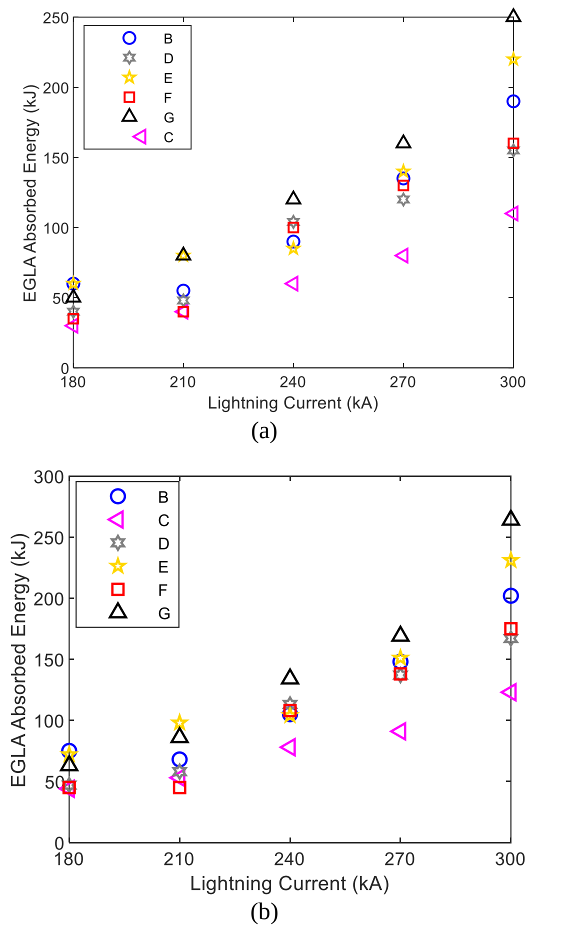

Fig. 10 EGLA absorbed energy for different lightning strikes (a) nonlinear grounding system (b) frequency grounding system

4 Conclusions

In this paper, the effect of the frequency behavior of the grounding system on the performance of the transmission line and the proper placement of the EGLA was investigated. the obtained results have been represented as follows:

- The proposed results represented that using downstream shield wire and EGLA lead to no back-flashover occurrence on lower phases and double-circuit outages. Consequently, EGLA installation on lower phases is not necessary when downstream shield wire exists, and EGLAs are installed on other phases.
- By using three EGLAs in the upper and middle phases, the back-flashover reduction may take place. Installing four EGLAs leads to lower back flashover but it is costly compared to other situations. In this situation, the back-flashover rate for the frequency grounding system is zero, approximately.
- Using a nonlinear grounding system leads to more back return current compared to the frequency grounding system. The frequency grounding system's effect on the EGLAs is obvious, and the absorbed energy for the frequency grounding system is higher than the nonlinear grounding system.
- It is recommended that for service unavailability of transmission lines and surge arrester placement, the frequency grounding system has been modeled to achieve more precise results.

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