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Impact of Lighthning Stroke and Mitigation on a 132 kV Transmission Line Using ECSP

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***Abstract*—Lightning strikes are one of the main causes of power system trip-outs. When the overhead transmission line is hit by lightning, large currents propagate to the substation, resulting in severe problems. In this paper, the transmission line, metal oxide arrester and tower ere model in Electric circuit simulator program (ECSP). The paper analyses the 132kV transmission line behavior during a lightning stroke of 100kA. The transmission shielding wire failure and back flashover is simulated by injecting single stroke current on the top of the tower. Simulation results shows that the 132kV transmission line voltage and current after the lightning stoke are 1.12 MV and 5.60 kA respectively but with the introduction of a Metal-oxide lightning arrester, the voltage are current were reduced to 140.47 kV and 702.37 A respectively. The paper underscores the critical importance of lightning protection measures in safeguarding power system infrastructure and ensuring the safety of personnel operating in lightning-prone environments.**

***Keywords*—Lightning Stroke; Metal-oxide arrester; flashover, ECSP.**

I. INTRODUCTION

Lightning strikes pose a significant threat to power systems, including transmission lines operating at 132 kV and above [1]. These strikes are natural phenomena resulting from the build-up and discharge of electrical energy in the atmosphere. When a lightning strike occurs, it can have devastating effects on power infrastructure, leading to equipment damage, downtime, and safety hazards [2]. Lightning is typically caused by the build-up of electric charge in clouds due to atmospheric conditions, such as convective processes and moisture content. The discharge of this accumulated charge can result in a lightning strike. These events are more common in regions with specific weather patterns, such as thunderstorm-prone areas. The frequency of strikes can vary seasonally, with peak activity often occurring during summer months in many regions. Lightning currents are characterized by high peak amplitudes, and fast rise times. These characteristics can induce high voltages and currents in power lines, leading to equipment damage and insulation failures. It can also cause transient over voltages, insulation breakdown, and equipment failures in power systems [3]. This can result in service interruptions, equipment replacement costs, and safety risks to personnel. To mitigate the impact of lightning strikes, power systems employ various protection measures, including surge arresters (Metal oxide arrester), Sphere gap arrester, hom gap arrester, oxide film arrester, electrolyte arrester and lightning rods [4][5]. Mitigation measures play a crucial role in safeguarding equipment, ensuring continuity of service, and reducing the risks associated with lightning-induced damage. One of the primary reasons for implementing mitigation measures is to protect critical equipment within the power system. By employing Metal oxide arrester (surge protection devices), grounding systems, and other protective measures, the risk of equipment damage can be significantly reduced. Mitigation measures designed for lightning protection often contribute to overall system resilience against a range of environmental challenges, enhancing the system's ability to withstand adverse conditions. Transmission line arresters are increasingly used to prevent double-circuit failures resulting from lightning strikes. Typically, these arresters are installed at the three phases of one circuit in a double-circuit transmission line, optimizing protection and reducing the risk of damage caused by lightning-induced surges [6]. Many jurisdictions like IEEE, etc. have specific standards and regulations governing lightning protection in power systems [7][8][9]. Adhering to these standards and implementing recommended mitigation measures is not only a best practice, but also a legal requirement for power utilities. Compliance ensures that the power system meets industry standards for reliability, safety, and performance. Numerous researchers have studied the optimum size, reliability, etc. of metal-oxide arrester (surge arrester). Reference [10] focused on the application of surge arresters in the context of 750kV transmission lines. Through rigorous experimentation and analysis, they identified the optimal size and placement of surge arresters, ensuring optimal performance and protection against voltage surges. This research not only contributed valuable insights into surge arrester optimization but also underscored their critical role in enhancing the resilience of ultra-high-voltage transmission infrastructure. Reference [11] examined the effectiveness of surge arresters designed for 500kV DC gas-insulated wires, highlighting their role in mitigating transient over-voltages and ensuring system stability. Building on this, Reference [6] reinforced their effectiveness in controlling switching over-voltages, reducing equipment damage risks. Reference [12] adopted a probabilistic approach to assess the reliability and failure risk of surge arresters. By analyzing various probabilistic models and scenarios, they provided valuable insights into the factors influencing surge arrester performance and longevity. This probabilistic analysis served as a valuable tool for engineers and operators to assess and mitigate the potential risks associated with surge arrester failures, thereby enhancing the overall reliability and safety of high-voltage systems. Given the unpredictable nature of lightning strikes, awareness, and preparedness are crucial for power system operators. This includes monitoring weather conditions, implementing robust protection systems, and having emergency response plans in place. In this paper, the behavior of lightning stroke on a 132kV transmission line and the performance of a metal-oxide surge arrester are analyzed.

II. LIGHTNING PHENOMENON AND INDUCED CHARGE ON A TRANSMISSION LINE

Lightning strikes are natural electrical phenomena that are formed due to the build-up of electric charges within clouds or between clouds and the ground. This build-up occurs primarily in thunderstorm conditions where strong updrafts and downdrafts within clouds lead to the separation of positive and negative charges [13]. When the charge separation reaches a critical point, it results in an electrostatic discharge in the form of lightning. This discharge can occur within a cloud (intra-cloud lightning) or between clouds (cloud-to-cloud lightning). The strikes are characterized by high peak currents, fast rise times, and short durations [14]. The peak current of a lightning strike can range from several thousand to hundreds of thousands of amperes, carrying a substantial amount of energy. Lightning channels are typically formed by a series of stepped leaders and return strokes. The stepped leaders are the initial paths of ionized air that extend from the cloud toward the ground or from one cloud to another. When a stepped leader makes contact with a conducting object (such as a tall structure or the ground), it completes the circuit as shown in figure 1, leading to a return stroke that produces the visible flash of lightning. The rapid flow of current during a lightning strike results in intense heat and light emission. This heat can exceed 30,000 degrees Celsius, causing rapid expansion of air and generating shock waves (thunder) that are heard as thunderclaps. When lightning strikes a transmission line as shown in figure 2, it can induce transient over-voltages, electromagnetic interference, and thermal effects which can exceed the equipment's rated voltage, cause insulation breakdown, flashovers along and, temporary or permanent outages.

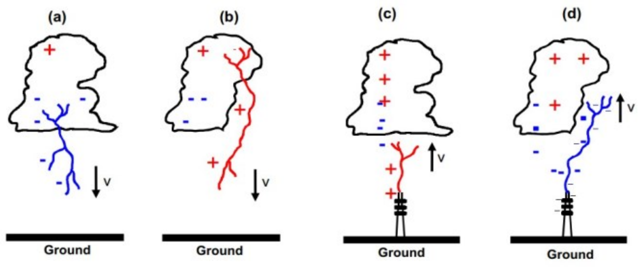

Fig.1. Forms of flashes of lightning to the ground [15]

The highest values of induced voltage in a direct lightning stroke may be determined since it will produce voltage on the wire [16]. Lightning parameter used to determine the voltage and current that lightning will produce into an elevated transmission line is shown in equation 1.

$$Ug = 25\,\frac{I \times HC}{S} \tag{1}$$

where Hc is the average height of the wire in meters, S is the distance between the lightning and the wire (in meters), and Z is the impedance of the transmission line, Ug is the highest voltage that lightning may cause, often not exceeding 100 kV.
When the transmission line is not linked to an earth line, the following equations can be used to determine the lightning current that results in the insulator string flashover as shown in equation 2.

$$I = \frac{U50\%}{100} \tag{2}$$

The current on the tower and the ground impedance cause the tower voltage to increase when lightning strikes the transmission line or towers. Due to this event, the voltage is electromagnetically coupled and propagation through the transmission line. A tiny portion of this voltage is induced in the phase conductor. If the voltage differential across the insulator rises over a certain threshold, an overvoltage is seen in the insulator, and causing a flashover or back flashover.

Fig. 2: Lightning stroke on a transmission tower

III. MATERIAL AND METHOD

III.A Electric Circuit Software Program (ECSP)

The Electric Circuit Simulator (ECS) software is an online tool for modeling and studying electrical power circuits and transient events. It addresses transmission line modeling, optimal power flow, short circuit, arc, transient stability, relay coordination, flash, load flow, cable capacity and other electrical engineering problems. Any organization, from a small power system to a large one, can customize its modular adaptability to meet their demands. As a result, the ECSP-designed and built operation technology makes this software the most comprehensive analytical tool for power system design, simulation, operation, monitoring, and automation. ECS is utilized in power systems of various sizes and industries, including renewable energy, nuclear power plants, transportation, smart grid solutions, and others. The ECSP integrating system permits the analysis of a wide range of electrical power systems.

III.B Method

The paper analyzed the impact of lighting stroke and its mitigation on a 132kV transmission line using Online Electric Circuit Software Program (ECSP). The transmission system and Metal oxide arrester parameters are shown in Tables 1 and 2.

The procedures of the research consist of several steps;

- Study of lighting Phenomenon and induced charge in a transmission Line
- Modeling and simulation of the transmission line, tower and insulator in OECS program.
- Modeling and simulation of the Metal Oxide lightning arrester
- Analyzed the impact of 100 kA lighting stroke and the mitigation using Metal oxide lightning arrester.

III.B.1 The 132kV transmission line, tower and insulator in OECS

In the study, the transmission line used is specified as a 132 kV line that spans 46 km in length, as depicted in Figure 1 and used in the study. The transmission system only presented two towers with 260 m between them. The parameters of this transmission line are outlined in Table 1. The transmission tower is also modeled and described, featuring a single-phase conductor with an insulator, as illustrated in Figure 3. The tower's height is characterized using inductivity measurements. Specifically, the arm of the tower is described with an inductivity of 6.4 mH. Additionally, the inductivity from the foot of the tower to the arm of the tower and from the arm to the top of the tower is noted as 25 mH and 3 mH, respectively as shown figure 4. These details provide a comprehensive understanding of the transmission line and tower configuration being studied. The tower footing resistance used for the study is 5Ω.

The insulator is linked in parallel to the voltage control switch. The insulator voltage capacity to withstand lightning is computed with equation 5.

$$V_o = 0.9\left(400 + \frac{710}{t^{0.75}}\right) d \qquad (5)$$

Where Vo is flashover voltage in kV, t is the time elapse after the lightning stoke in µs while d is the length of gap between the arc horn in meters (m).

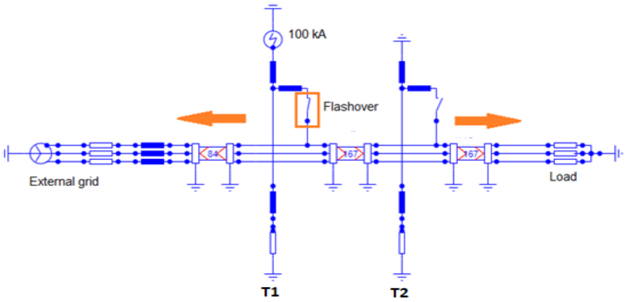

Fig 3: 132kV transmission line (46 km) showing two tower with one arm and insulator

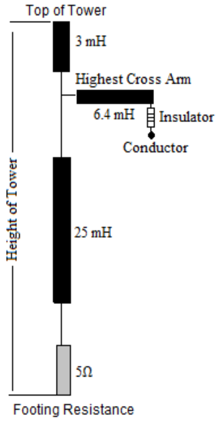

Fig 4: One arm of the Tower used on in the simulation (ECSP)

TABLE 1: TRANSMISSION LINE PARAMETERS USED IN THE SIMULATION

S/N	Description	Value
1	Ohmic Resistance/m	0.00004 Ω/m
2	Surge Impedance	18Ω
3	Inductivity/m	0.06µH
4	Capacity/m	185.313 pF
5	Line length/m	100/m
6	Line Length	46km

III.B.2 Metal Oxide Lightning Arrester

A metal oxide arrester, also known as a surge arrester is an essential component in electrical systems designed to protect equipment from overvoltage conditions caused by lightning strikes or switching surges in transmission and distribution line [3]. Metal oxide arresters function by diverting excessive transient voltages to ground, thus preventing damage to connected equipment. They provide a low-impedance path for the surge current to flow, effectively limiting the voltage across the protected equipment. When a surge occurs, the voltage across the arrester increases, causing the metal oxide discs to conduct heavily. This action creates a low-resistance path to divert the surge current to ground, thus protecting downstream equipment from experiencing damaging voltage levels. Arresters avoid lightning flashovers since transmission line insulation voltage is higher than the residual voltage developed across the arrester due to back flashover [17]. The characteristics of the metal oxide arrester used in the study are shown in Table 2. The energy discharge by the arrester during back flashover can be estimated using equation 6;

$$W_A = i_A e_A \tau \qquad (6)$$

where iA is the arrester current (A), eA is the arrester discharge voltage (V) and τ is the time constant. The time is estimated using equation 7.

$$\tau = \frac{Z_g}{R_i} T_s \qquad (7)$$

where Ts is the ratio of the span length to the velocity of light, Zg is the impedance (Ω) of the ground wire and Ri is the footing resistance (Ω).

TABLE 2: CHARACTERISTICS OF THE METAL OXIDE ARRESTER USED IN THE SIMULATION

S/N	**Parameters**	**Values**
1	MCOV(Peak)	2x10 V
2	*Uprot /MCOV*	2.481
3	R.saturation (ohms)	0.741
4	R. blocking (ohms)	5. 024x 10^7
5	U at 0.5kA	5x 10^3
6	U at 2.0KA	5 x 10^3
7	U at 10KA	5.56 x 10^3

IV. RESULTS AND DISCUSSION

IV.A 32KV Transmission line Voltage and current before the lightning Stroke

Figure 5 illustrates the voltage waveform characteristics of a 132 kV transmission line just before experiencing a 100 kA lightning strike. The phase voltage recorded at the load terminal was measured at 130.88 kV, showcasing the stable condition of the electrical system before the lightning event. This voltage measurement is crucial as it provides insight into the normal operating parameters of the transmission line. Subsequently, Figure 6 displays the current waveform depicts a perfect waveform with a current level of about 652.81 A.

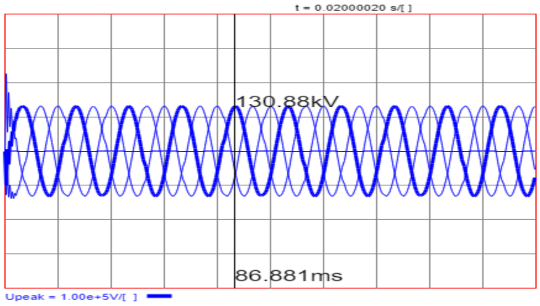

Fig. 5: Line voltage before the lightning stroke

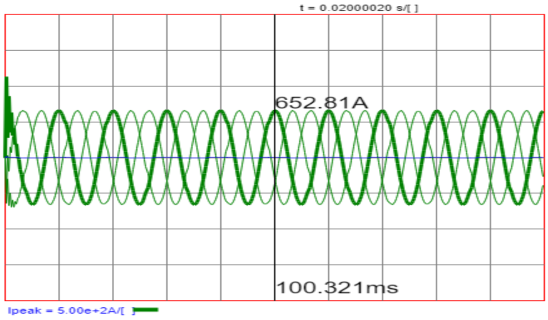

Fig 6: Line current before the lightning strokes of 100KA

Iv.B Voltage And Current Waveform On The 132 Kv Transmission Line After The Lightning Stroke Of 100ka

When a lightning stroke of 100 kA impacts the tower, the voltage surge observed on the top of the tower reaches 1.43 MV. This surge in voltage is a direct result of the high-energy discharge associated with the lightning strike. The power generated by this stroke propagates along both sides of the transmission line, as depicted in Figure 3, highlighting the widespread impact of the lightning event on the surrounding infrastructure. The intensity of the 100 kA lightning stroke causes a flashover on the tower insulator, as indicated in Figure 3. This flashover occurs due to the sudden increase in voltage across the string insulator, surpassing its insulation capacity and leading to a breakdown in the insulating properties. Figure 7 captures the immediate aftermath of the lightning strike, showing a rapid voltage spike of 1.12 MV on the transmission line. This spike gradually diminishes over time, stabilizing at around 130.08 kV approximately 5.111 milliseconds after the lightning stroke. Simultaneously, the line current experiences a substantial increase to about 5.60 kA following the 100 kA lightning stroke, as evidenced in Figure 8. The sudden rise in voltage and current levels can lead to equipment damage, insulation failures, and potential hazards to personnel working in the vicinity of the transmission line.

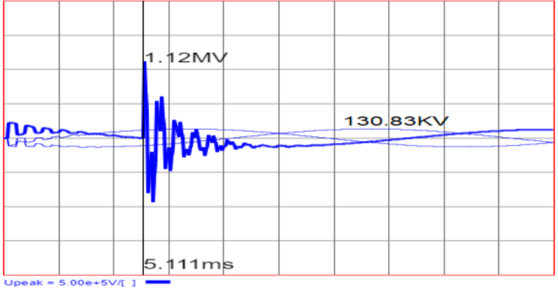

Fig. 7: Transmission Line voltage after a 100kA lightning stroke

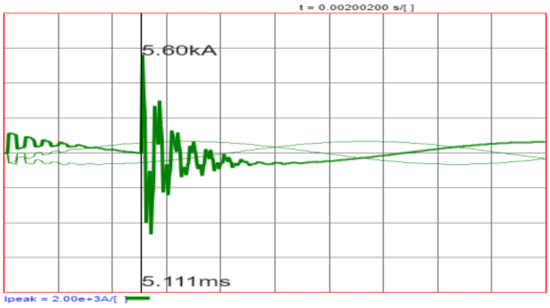

Fig.8. Transmission line current after a 100kA lightning stroke

IV.C Impact of Metal Oxide Lightning Arrester on the Transmission line

Figure 9 illustrates the impact of the metal oxide arrester on the system's voltage characteristics. It is observed that the line voltage reduces significantly from 1.12 MV to 140.47 kV when the metal oxide arrester is applied. This reduction ensures that the voltage to remains within the standard limits prescribed for the transmission line, thereby preventing flashovers and insulation failures. Similarly, Figure 10 presents the effect of the metal oxide arrester on the system's current. With the arrester in place, the line current is reduced from 5.60 kA (or 5600 A) to 702.37 A. This reduction in current ensures that the current remains within the safe operating limits of the transmission line, minimizing the risk of flashovers and protecting the equipment from damage. The successful application of the metal oxide arrester achieves the objective of the study, which is to provide effective protection against over-voltages and currents induced by lightning strokes. By mitigating the impact of lightning-induced disturbances, the arrester enhances the reliability, safety, and performance of the power system, ensuring uninterrupted power supply and minimizing downtime due to lightning-related incidents

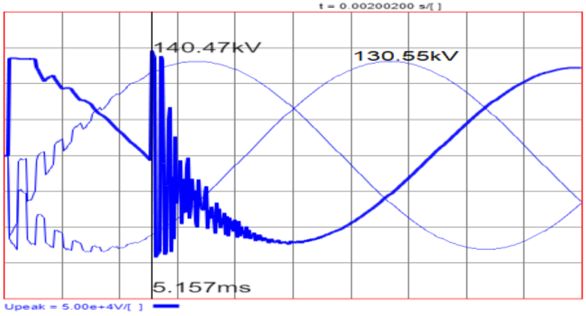

Fig. 9: Transmission line voltage after lightning stroke of 100kVA with Metal-oxide arrester

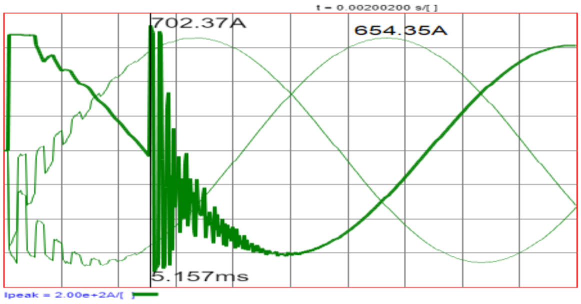

Fig. 10: Transmission line current after lightning stroke of 100kVA with Metal-oxide arrester

V. CONCLUSION

The paper investigates and analyses the impact of a 100 kA lightning stroke on a 132 kV transmission line and the capacity of the metal oxide arrester to withstand the single stroke lightning discharge energy during shielding wire failure and back flashover phenomena. The simulation results include a detailed analysis of voltage, current, and arrester performance associated with the 100 kA lightning stroke. The metal-oxide lightning arrester successfully diverts excessive transient voltages to ground, preventing damage to connected equipment. It provides a low-impedance path for surge current to flow, effectively limiting the voltage across protected equipment, as demonstrated and analyzed in the paper.

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