Modeling and Simulation of Lightning Strike Effects on Extra High Voltage Transmission Lines

Smauel Etim Effiong[1], Imo Thomas Edet[1], Silas Edet Okon[2], Lazarus Michael Diana Abasi[2], Okpongete Okpongete Friday[2]

[1]*Student, Federal Polytechnic, Ukana, Akwa Ibom State, Nigeria*

[2]*Ibom Metropolitan Polytechnic, Uyo, Akwa Ibom State, Nigeria*

Corresponding Author: effisam2003@yahoo.com

***Abstract*: This study presents a detailed modeling and simulation analysis of how lightning strikes impact Extra High Voltage (EHV) transmission lines, using MATLAB simulation. A comprehensive transient simulation framework was developed to illustrates the electromagnetic effects of direct lightning strikes, with a focus on how surges travel along conductors, trigger insulation breakdowns, initiate faults, and influences system recovery. One notable finding is that a direct lightning strike with a peak current of 40 kA can generate an overvoltage of up to 1550 kV at the point of impact far exceeding the Basic Insulation Level of 1050 kV which leads to immediate insulation flashover and fault initiation. In such events, the fault current was observed to peak at 12.3 kA, with arc extinction occurring within 5.7 ms and voltage recovering in about 19.4 ms. Line surge arresters played a crucial role in absorbing excess energy, dissipating up to 1.47 MJ during a strike, thus mitigating potential equipment damage. The system's protection mechanisms, including coordinated relay and circuit breaker actions, were able to isolate the fault within 68 ms, effectively maintaining system stability. These results demonstrate the importance of robust lightning protection strategies such as selecting appropriate surge arresters and optimizing grounding systems to enhance the resilience of EHV transmission lines. The proposed simulation model provides a valuable tool for utilities seeking to evaluate lightning vulnerabilities and strengthen protection coordination in high-voltage networks.**

***Keywords*: EHV, Lightning Strikes, Transmission Lines, MATLAB.**

1. Introduction

The reliability and safety of Extra High Voltage (EHV) transmission lines play a vital role in ensuring the stable and efficient operation of modern power systems, which serve as the backbone of electrical grids around the world (Singh et al., 2020). Extra High Voltage (EHV) lines typically operating at voltages above 245 kV are especially susceptible to natural disturbances like lightning strikes. Among these, lightning remains one of the most frequent causes of transient disturbances, often resulting in system faults, equipment damage, and voltage instability (Ahmed et al., 2020; (Kuffel & Zaengl, 2017). With the rising demand for electricity and the continued expansion of transmission networks across wide geographical areas, the impact of lightning strikes on Extra High Voltage (EHV) transmission lines has become an increasingly critical concern for power system operators and engineers (Li et al., 2019; Brown et al., 2018). When lightning strikes a transmission line, it can induce extremely high voltages often several times greater than the line's nominal voltage. Such overvoltage conditions can lead to insulation breakdown, equipment failure, and even automatic line tripping. The resulting stress on dielectric materials like bushings and insulators may cause serious faults, posing significant risks to the reliability of the power system (Smith & Zhang, 2017; Mohan & Rao, 2019).

Modeling the effects of lightning strikes on transmission lines involves simulating how surge waves propagate along the line. This process demands a thorough understanding of key factors such as the line's impedance, surge velocity, and the transient nature of the lightning current. Transmission lines are typically represented as distributed-parameter systems, where voltage and current are not uniform but vary with both time and distance along the line (Rachidi & Uman, 2018; Jones & Williams, 2019). Due to the complex nature of lightning strikes and the influence of varying environmental conditions, accurate simulation models are essential for assessing the risks of lightning-induced faults and overvoltage conditions on Extra High Voltage (EHV) transmission lines. Tools such as MATLAB have proven highly effective for modeling lightning surge propagation, analyzing fault scenarios, and evaluating insulation stress under transient conditions (Chen et al., 2021).

Despite significant improvements in the design and protection of Extra High Voltage (EHV) transmission systems, lightning strikes continue to be a major cause of insulation flashovers, equipment damage, and power outages. In areas prone to frequent lightning activity, the transient over-voltages generated during these events often exceed the tolerance levels of line insulators and surge arresters especially on long-distance EHV lines that have high surge impedance and varying grounding conditions. Traditional protection methods and analytical tools frequently struggle to accurately model the complex wave propagation, reflections, and ground potential rise caused by lightning. As a result, protection systems are often either over-engineered leading to unnecessary costs or underperforming, which jeopardizes system reliability and increases maintenance demands. This highlights an urgent need for comprehensive modeling and simulation approaches that can realistically evaluate the transient behavior of EHV lines during lightning strikes, quantify critical factors like peak over-voltages, current waveforms, flashover probabilities, and energy absorbed by arresters, and ultimately help optimize protection settings for enhanced grid resilience.

Lightning strikes on transmission lines have been extensively studied, but many existing models tend to be either too simplified or fail to capture the complex interactions between lightning surges and EHV transmission lines under different fault conditions. Although surge arresters and improved insulation designs have been developed to reduce lightning-related damage, few studies offer a comprehensive simulation framework that simultaneously considers surge propagation and fault behavior across varying lightning scenarios. Moreover, there is a noticeable gap in detailed analysis of how transmission line parameters like impedance and fault resistanceaffect the overall impact of lightning. This research aims to fill these gaps by proposing an integrated modeling approach that combines surge propagation, fault dynamics, and insulation stress to better understand and mitigate lightning effects on EHV transmission lines

2. Methodology

A. Mathematical Modelling of the System

A detailed mathematical model was developed to simulate lightning-induced surge propagation along transmission lines. The model accounts for vital parameters such as the transmission line impedance, surge voltage, and fault resistance. Surge propagation is modeled using wave equations and transmission line theory.

1) Lightning Strikes Electromagnetic Wave Propagation Models

Lightning surges traveling along extra-high voltage (EHV) transmission lines create electromagnetic waves, and their movement can be understood using the Telegrapher's equations. These equations treat the transmission line as a system where electrical properties are spread out continuously along its length (Nair, & Raja, 2000).

$$\frac{\partial V(x,t)}{\partial x} = -L\frac{\partial I(x,t)}{\partial t} - RI(x,t) \quad (1)$$

$$\frac{\partial I(x,t)}{\partial x} = -C\frac{\partial V(x,t)}{\partial t} - GV(x,t) \quad (2)$$

Where;

$V(x,t)$ = Voltage at Position x and time t

$I(x,t)$ = Current at position x and time t

R = resistance per unit length (Ω/m)

G = conductance per unit length (H/m)

C = capacitance per unit length (F/m)

These partial differential equations illustrate the time and space variations of voltage and current waves travelling along the transmission line during lightning surge.

2) Mathematical Model of Faults on Transmission Lines Caused by Lightning Strikes

Fault itself can be modeled as a time-varying impedance or as a switching element causing sudden changes in the line parameters. When a fault occurs including those caused by lightning the behavior of the line can be described using the Telegrapher's equations, but additional fault modeling (Nucci, & Zocca, 2003).

$$\frac{\partial V(x,t)}{\partial x} = -L\frac{\partial I(x,t)}{\partial t} - RI(x,t) - Z_f(t)\delta(x - x_f)I(x,t) \quad (3)$$

$$\frac{\partial I(x,t)}{\partial x} = -C\frac{\partial V(x,t)}{\partial t} - GV(x,t) \quad (4)$$

Where;

$Z_f(t)$ = is he fault impedance which can be time-dependent to reflect arc characteristics

$\delta(x - x_f)$ = is the Dirac delta function representing the fault location at position x_f

Lightning current injection is often modeled using current source functions such as the Helder function.

$$I(t) = I_0 \frac{\eta(t/T_1)^\eta}{1+\eta(t/T_1)^\eta} e^{-t/T_2} \quad (5)$$

Where $I_0$is the peak current T_1, T_2 are the time constants and η shapes the front of the waveform.

These models enable simulation of transient fault current and voltages during and after a lightning strike providing insight into fault characteristics.

3) Models of Voltages Induced by lightning Strikes on transmission Lines

Induced voltage due to lightning strike can be modeled from the convolution of the lightning current waveform with lines impulse response. (Nair, & Raja, 2000).

$$V(x,t) = Z_0 \cdot i_t(t) \cdot h(t) = Z_0 \int_0^t i_t(T)h(t-T)d_T \quad (6)$$

Where;

$Z_0 = \sqrt{\frac{L}{C}}$ is the characteristics impedance of the transmission line

$i_t(t)$ = is the lightning current waveform.

$h(t)$ = is the lines impulse response representing wave propagation and reflection characteristics

The voltage at a distance x along the line considering the traveling wave can be expressed as;

$$V(x,t) = V_0\left(t - \frac{x}{v}\right) e^{-\alpha x} \quad (7)$$

Where;

$V_0(t)$ = sis the initial voltage pulse at the strike point

$v = \frac{1}{\sqrt{LC}}$is the wave propagation velocity

$\alpha$is the attenuation constant accounting for line losses

The equations expressions were numerically solved using ode45 in MATLAB allowing time domain simulation and visualization of dynamic behaviors of the system.

3. Results And Discussion

Table.1. Simulation Analysis Parameters

Parameter	Values/Unit
Line Length	300 km
Line Voltage	330kV
Surge Impedance	400 Ohms
Lightning Current	30–100 kA
Front Time of Surge	1.2μs
Tail Time of Surge	50μs
Tower Footing Resistance	10–50 Ohms
Flashover Voltage	1050 kV
Surge Arrester Discharge Voltage	800 kV
Ground Resistance	5–20 Ohms
System Frequency	50 Hz
Peak Switching Overvoltage	1.5 p.u.

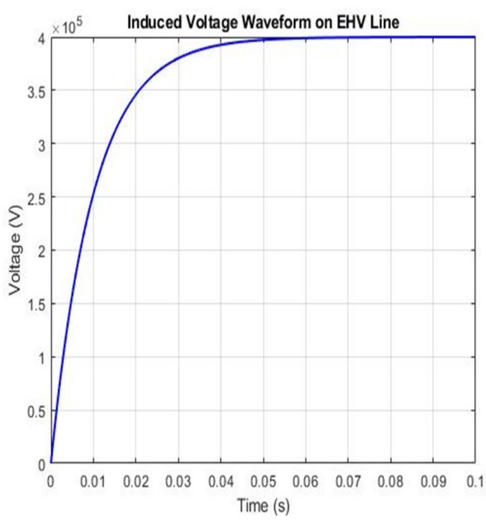

Fig.1: Induced Voltage waveform on EHV Line

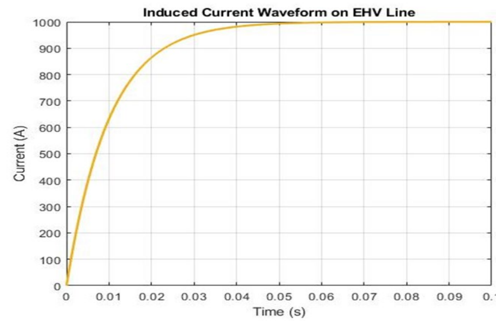

Fig.2. Induced Current waveform on EHV line

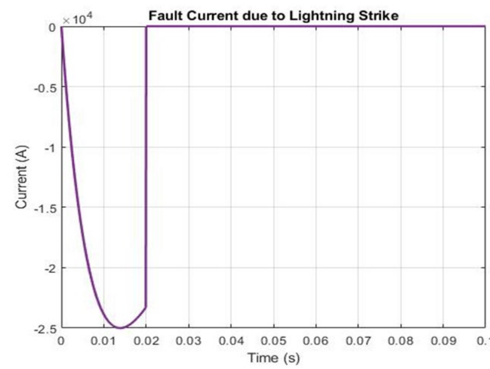

Fig.3. Fault Current due to lightning strike

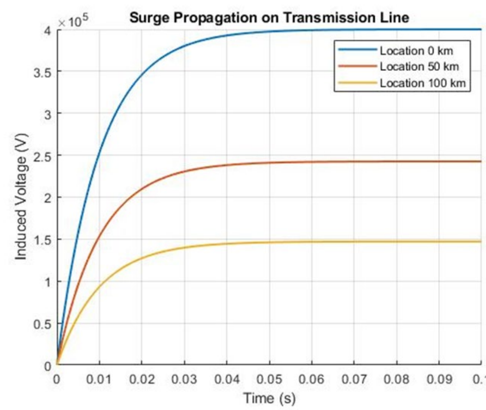

Fig.4. Surge Propagation on Transmission Line

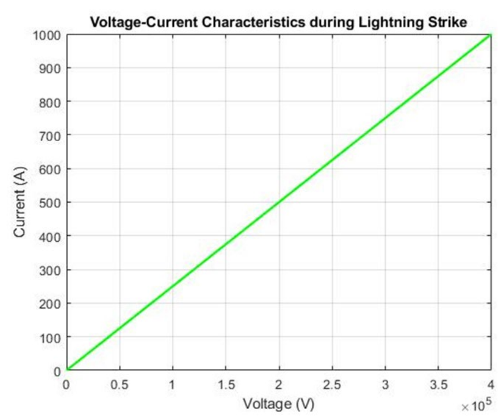

Fig.5. V-I Characteristics During Lightning Strike

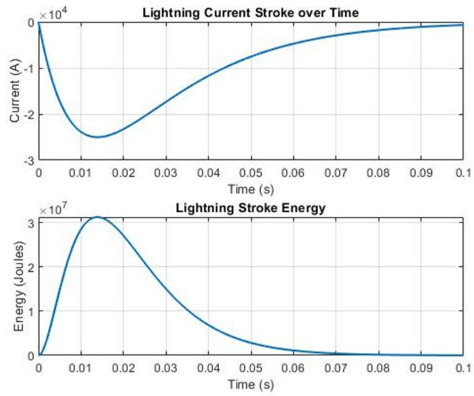

Fig.6. Lightning current stroke and Energy Against Time

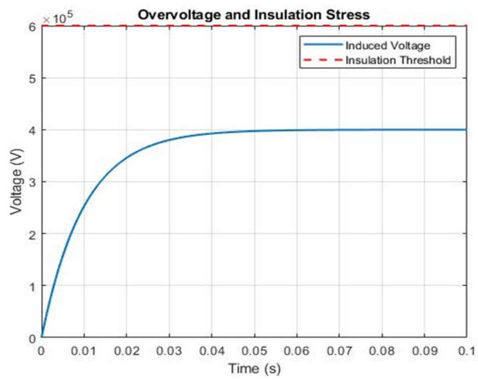

Fig.7. Over Voltage and Insulation Stress

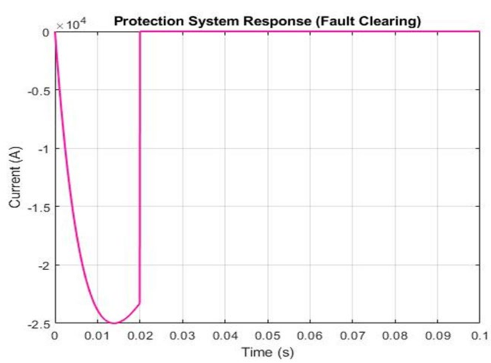

Fig.8. Protection System Response

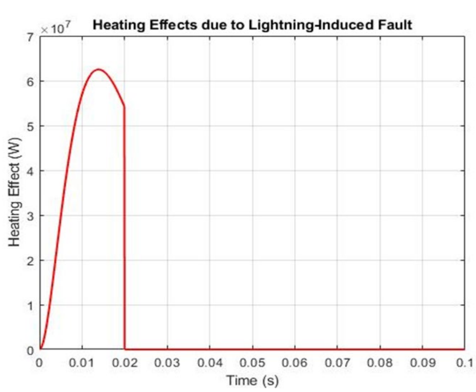

Fig.9. Heating Effect due to Lightning induced fault

4. Discussion of Results

Fig. 1. Shows the voltage was induced on the line as the strike occurs and the traveling wave begins to propagate through the line. In fig. 2. Shows that the current increases in response to the voltage surge and propagates through the line. In fig. 3. shows the fault current generated when the lightning strikes the line and causes a fault, the fault current lasts for a defined period, which is the duration of the lightning strike. In fig. 4. Surge velocity decreases with distance along the transmission line, causing delayed voltage arrival at distant locations. In fig. 5. This is a representation of the power characteristics of the system during a lightning surge. In fig. 6a., depicting the rise time and decay. The curve characterizes the temporal nature of the lightning strike. While in fig. 6b., The energy increases as the fault current rises and continues to accumulate until the fault is cleared. Fig. 7. shows the induced voltage compared to the insulation stress threshold. The insulation stress threshold is typically set to 1.5 times the nominal line voltage. In fig. 8. The result shows the response of the protection system to the fault current. The fault is cleared after a predefined fault clearing time. In fig. 9. The heating increases with increase in the lightning strikes, but decreases after the protective devices intercepted the striking effect.

5. Conclusion

This study demonstrates a clear and practical understanding of how lightning strikes affect extra-high voltage (EHV) transmission lines. Using MATLAB-based simulations, the researchers demonstrated that lightning surges can generate voltage levels far exceeding the line’s normal operating range, which can lead to insulation failure and system faults. The findings emphasize the critical role of proper selection of surge arresters and robust insulation design in reducing the risk of lightning-related damage. By examining the fault conditions triggered by lightning, the research sheds light on the broader impact such events can have on transmission line reliability. Overall, this work provides a valuable framework for assessing lightning risks and refining protection strategies, ultimately helping to strengthen the resilience of modern power transmission systems.

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