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Exploring how lightning interacts with a lightning rod (surge arrester) through copper wiring and how lightning waves reflect in the earth

Author Amirhosein Safian

Affiliation : Department of Electrical Engineering, Arak University of Technology, Markazi province, Iran

Abstract

Lightning strikes and switching fluctuations are significant contributors to voltage surges within power systems. When a high-voltage transmission tower is struck by lightning, it can lead to serious damage to insulation and other components connected to the electrical network. To safeguard against such occurrences, various types of surge arresters are employed to protect the insulators on transmission and distribution lines, as well as the electrical equipment linked to these networks. In this article, we will first outline the critical factors involved in the protection of power systems against lightning-induced surges and fluctuations. Understanding these factors is essential for implementing effective safety measures. Following this foundational discussion, we will conduct a detailed simulation to analyze the behavior of surge arresters under lightning strike conditions. The results of this simulation will provide valuable insights into their effectiveness in mitigating damage and ensuring the reliability of power systems.

Keywords: Lightning, lightning rod, distribution tower, surge arrester



Introduction

Lightning is a natural phenomenon characterized by an electrical discharge that occurs either between charged clouds, between clouds themselves, or among different charge centers within the same cloud. It is one of the most common and frequent causes of over-voltage conditions and insulation failures in power systems. Both lightning and switching surges significantly contribute to outages in power transmission and distribution networks. Understanding the characteristics of lightning-induced over-voltage is crucial for designing effective protection schemes for power systems. It is widely recognized that taller structures are more likely to experience lightning strikes, as the probability of a strike increases with height [1]. This inherent risk is particularly relevant for high-voltage transmission towers, which, due to their significant elevation, present a shorter path for lightning to reach the tower's apex, making them especially vulnerable to direct strikes [2].

Surge Protection Circuit Principle And Design

Surge protection circuit is the one referred by many as protector for voltage spikes in AC grid lines; however it is not limited particularly in AC grid lines [2]. Surge protector or surge protection device is a device that will provide surge suppression or voltage spike suppression so that sensitive devices will not get damage [1]. Surge protector can handle voltage spikes as high as some kilovolt range (depending on the type of surge protection device). There are also surge suppressors that are intended only to handle few hundred volts, and so on. Although surge protector is design to withstand to high voltage spikes in a short period of time, it is not rated to handle high voltages in longer duration.

What Is Surge?

A surge refers to a sudden increase in level or magnitude beyond a normal or standard value. In electrical terms, it typically describes a voltage transient, surge, or spike. These voltage surges are not permanent events; they occur over a brief period but can be powerful enough to damage devices if no protective measures are in place. Voltage surges can arise not only in power lines but also in circuits with inductive properties. However, the surges that occur in power lines are often the most destructive, potentially reaching levels in the kilovolt range. For instance, a voltage surge on an AC power line can have significant implications for connected devices. To mitigate the risk of damage from these surges, surge protectors are commonly installed in homes, offices, and other buildings. These devices are typically placed in areas where multiple appliances or devices draw power, ensuring that all connected equipment is shielded from line surges and spikes. This strategy is known as universal surge protection. While universal surge protection is effective, it may not be necessary if each appliance or device is equipped with its own local surge protection circuit. In such cases, the individual protections can suffice to safeguard against voltage transients, reducing the need for a centralized surge protection system [1-3].

Effects on electrical installations

Lightning poses a significant threat to electrical and electronic systems, inflicting damage on critical components such as transformers, electricity meters, and various electrical appliances in both residential and industrial settings. The financial burden associated with repairing lightning-related damage can be substantial. However, assessing the full extent of the consequences can be challenging, particularly when considering the disturbances caused to computers and telecommunication networks, as well as the faults that may arise in programmable logic controllers and control systems. Oftentimes, the operating losses incurred can far exceed the repair costs of the equipment itself [3]. Lightning strikes exert their influence in two main ways: first, through direct impacts on buildings and second, via indirect effects that can occur through electric power lines. For example, a lightning strike may hit an overhead electric power line supplying a building, resulting in overcurrent and overvoltage that can propagate several kilometers from the point of impact. Additionally, when lightning strikes near power lines, the electromagnetic radiation generated can induce high currents and overvoltages throughout the electrical supply network, creating hazardous conditions for connected devices.

Surge Arrester Models for Fast Transients

To mitigate these risks, accurately modeling the behavior of metal oxide surge arresters in response to lightning strikes is essential. Such modeling must consider their dynamic behavior, which is represented by non-linear voltage-current (V-I) characteristics. The waveform of the residual voltage generated by a surge arrester is heavily influenced by the front time of the lightning current, exhibiting an increase as the front time decreases. Notably, the residual voltage peaks just before the peak of the lightning current itself. Research conducted by the IEEE indicates that the residual voltage increases by approximately 6% when the front time is reduced from 8 microseconds to 1.3 microseconds. Furthermore, for front times shorter than 4 microseconds, undesirable voltage spikes can manifest, sometimes exceeding the maximum residual voltage of the lightning arrester. These spikes are typically influenced by parasitic inductance, which can arise from the loops created in the measuring device circuitry. Numerous contributions have been made to improve models that simulate the dynamic performance of surge arresters. A key challenge in this modeling process is accurately determining the necessary parameters for the models. For a circuit model to be reliable in studying the behavior of lightning arresters, it must account for various features, including front time and frequency, to ensure that results align with

expected outcomes. By addressing these modeling intricacies, we can enhance the effectiveness of surge protection techniques and contribute to more resilient electrical systems.

IEEE model

The circuit model of the lightning arrester proposed by the IEEE is shown below:

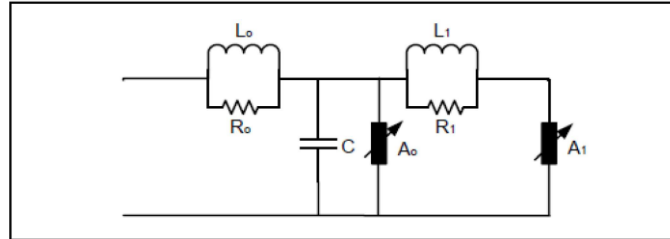


Figure (1) Circuit model of the lightning arrester by IEEE

The model proposed by the IEEE group characterizes the nonlinear voltage-current (V-I) behavior of a lightning arrester using two nonlinear resistors, designated as A0 and A1, as illustrated in Figure 1. These resistors are connected in parallel and are separated by an R-L filter that exhibits low impedance for currents with slow front times. Conversely, for currents with fast front times, the filter's impedance increases, allowing a greater proportion of the current to flow through the nonlinear resistor A0. Due to A0's greater current-carrying capacity compared to A1, the circuit model generates higher voltages, reflecting the dynamic behavior of the lightning arrester accurately. To effectively select the parameters for this model, specific formulas have been developed. These formulas take into account the height of the lightning arrester and the number of parallel columns of metal disks within the device. The inductance L1 and resistance R1 of the filter between the two nonlinear resistors are defined as follows:

- $L1=15 \text{ n}\mu$
- $R1=65 \Omega$

In these equations, dd represents the estimated height of the lightning arrester in meters, while nn denotes the number of parallel columns of metal oxide present in the arrester. Additionally, the inductance L0 is associated with the magnetic fields surrounding the lightning arrester, and the resistance R0 serves to stabilize the mathematical processing during computer-based model analysis. The capacitance CC reflects the capacity between the two terminals of the lightning arrester. The relevant equations for these parameters are:

- $L0=0.2 \mu\text{H}$
- $R0=100 \Omega$
- $C=100 \text{ pF}$

The nonlinear V-I characteristic of the resistors A0 and A1 can be estimated using the curves presented in Figure 2. This comprehensive approach to modeling the lightning arrester's behavior under dynamic conditions enables more accurate predictions and assessments of its performance during lightning events.

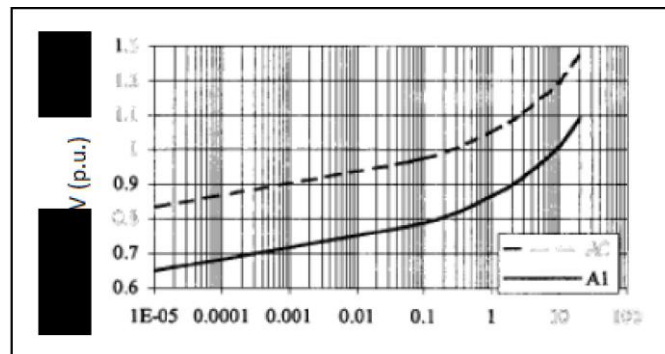
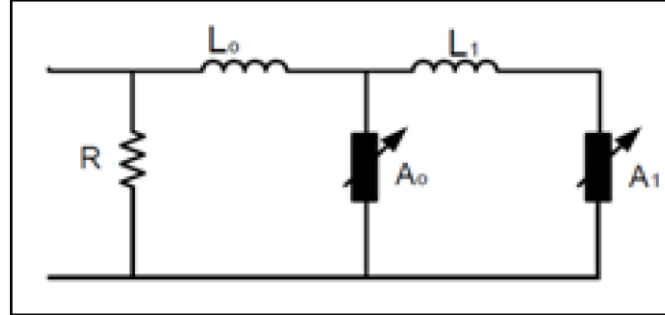


Figure (2) V-I characteristics for the nonlinear resistors A0 and A1

Pinceti-Giannettoni model

The Pinceti-Giannettoni circuit model (Figure3) is a simplified IEEE model. The calculation of the V-I characteristic is the same as that of the IEEE model. But the determination of the parameters is based on the electrical characteristics of the lightning arrester.



Figure(3) Circuit model of Pinceti-Giannettoni

When comparing the two models, Pinceti-Giannettoni's approach simplifies the representation of the lightning arrester by eliminating the capacitance component, as its influence on the model's behavior is considered negligible. Additionally, the two parallel resistors with their associated inductances have been replaced by a single resistor R_R (approximately in the megaohm range) connected between the input terminals. This modification helps to avoid numerical simulation issues while maintaining the core operating principles of the model, which are largely aligned with those of the IEEE.

The Pinceti-Giannettoni model is based on two fundamental rules:

1. **Identification of Nonlinear Resistors:** The nonlinear resistors A_0 and A_1 are identified using the current-voltage characteristics established in the IEEE model. This identification process refers specifically to the maximum residual voltage recorded during a test with an impulse current of 10 kA.
2. **Determination of Inductances:** The inductances in the model can be determined using the following equations:

$$L_1 = k_1 \cdot d$$

$$L_0 = k_2 \cdot d$$

Here, k_1 and k_2 are constants that depend on the specific design and materials of the lightning arrester, while d represents the estimated height of the arrester in meters. By streamlining the model in this way, Pinceti-Giannettoni's framework offers a more straightforward approach while still capturing the essential dynamics of lightning arresters under transient conditions. This allows for effective numerical simulations and practical applications in analyzing the performance of surge protective devices.

$$L_0 = \frac{1}{12} \frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}} V_n$$

$$L_1 = \frac{1}{4} \frac{V_{r1/T_2} - V_{r8/20}}{V_{r8/20}} V_n$$

Overview of Lightning Arrester Models

In evaluating the performance of lightning arresters, several models exist that provide varying levels of complexity and accuracy. Among them, the Pinceti-Giannettoni model and the proposed criteria for parameter selection stand out due to their emphasis on electrical characteristics over physical attributes.

Key Parameters:

- **Rated Voltage (V_n):** The rated voltage of the lightning arrester.
- **Residual Voltage ($V_r, 1/t_2 V_r, 1/t_2$):** This refers to the residual voltage measured for a lightning current with a front time of 1 microsecond ($1 \mu s$) at 10 kA.
- **Residual Voltage for 8/20 μs Current ($V_r, 8/20 V_r, 8/20$):** This is the residual voltage measured for a lightning current with a front time of 8/20 μs at 10 kA.

Model Characteristics

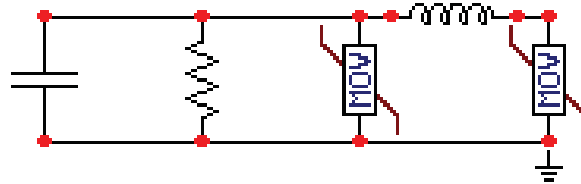
The proposed selection criteria for parameters in the Pinceti-Giannettoni model focus solely on the electrical data provided by the manufacturer rather than considering the physical characteristics of the lightning arrester. This approach distinguishes it from other models that may attempt to factor in manufacturing variances or physical designs. The equations for inductances L_0 and L_1 are rooted in their respective roles within the model. Specifically, the inductance L_1 is critical for identifying the dynamic behavior of the lightning arrester during lightning currents with fast rise times. As such, it is logical to align the values of these parameters with the manufacturer's specifications regarding lightning arrester performance under conditions similar to actual lightning strikes. Error analysis indicates that the discrepancies between the measured and calculated residual voltages are minimal for lightning currents with rise times ranging from 1 to 30 μs . Notably, this error diminishes further as the rise time approaches 8 μs , indicating improved accuracy with slower rise times.

Fernandez Model

Moving forward, the Fernandez model also draws inspiration from the IEEE arrester model. However, it simplifies certain aspects for practical applications. In particular, the inductance at the input can generally be neglected, while the resistance is defined as 1 $M\Omega$. This model's approach allows for easier integration into numerical simulations and applications while still maintaining necessary dynamics for effective surge protection against lightning strikes. The simplicity of the Fernandez model can be advantageous in scenarios where computational resources are limited or where quick estimations of lightning arrester performance are needed.

Concluding Remarks

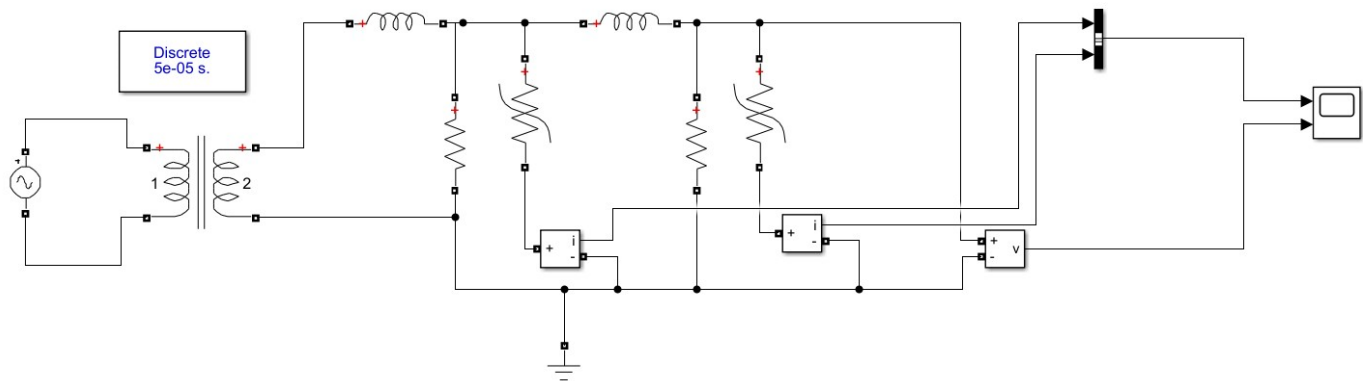
The evolution of lightning arrester models reflects an ongoing effort to enhance accuracy and reliability in electrical systems. By focusing on electrical characteristics, models like those proposed by Pinceti-Giannettoni and Fernandez offer valuable tools for engineers and designers tasked with improving the resilience of power systems against lightning-induced surges.



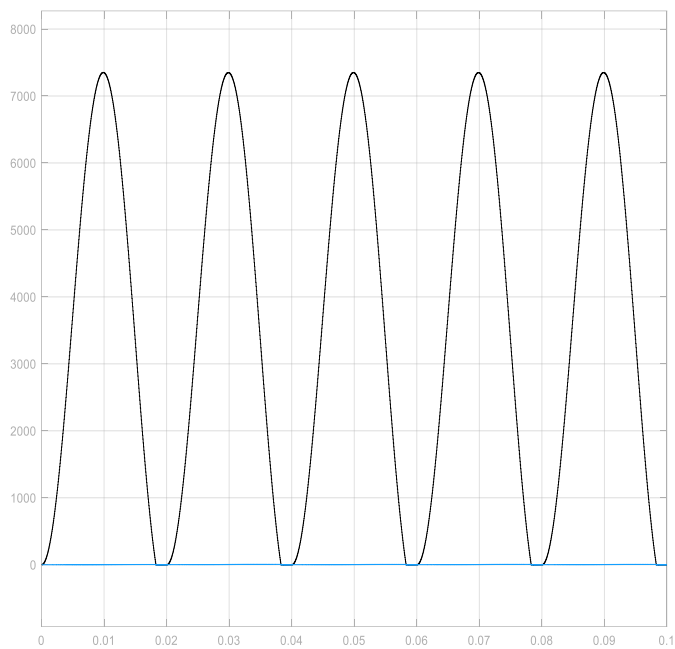
Figure(4) Model of Arrester Fernandez

SIMULATION

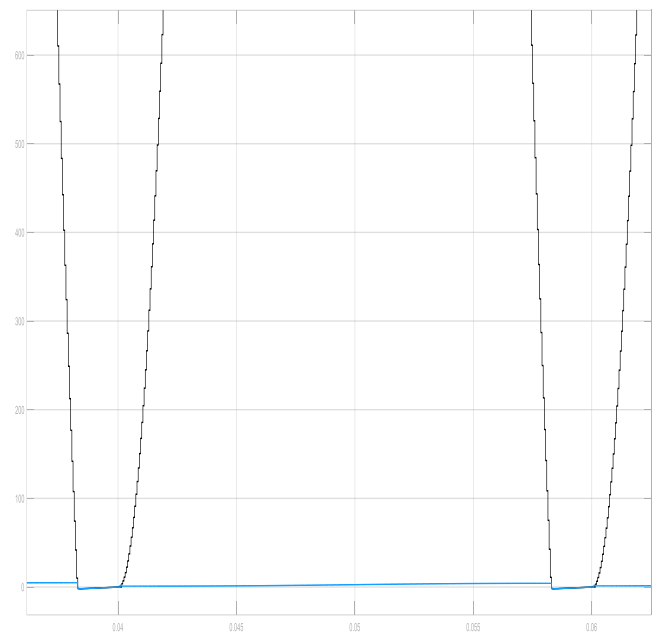
There are two nonlinear resistance in this model with two induction with $L_0=7.52e-3$ and $L_1=22.58$ (H) and big impedance in parallel with $R=1M\Omega$ ms. source voltage is 240 volts with the 50 hz frequency. the transformer make the voltage to 400K volts for better simulatuin calculation. current of the two nonlinear resistance would measured and showed in scope .and the final voltage has been measured with voltage measurement too. fig 7 shows the wave picture of below circuit.



Figure(5) single phase lightning arrester model

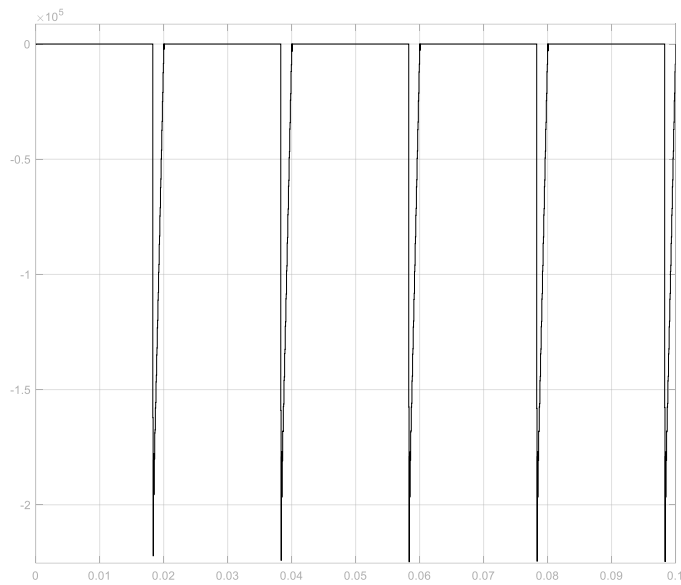


Figure(6) current waves

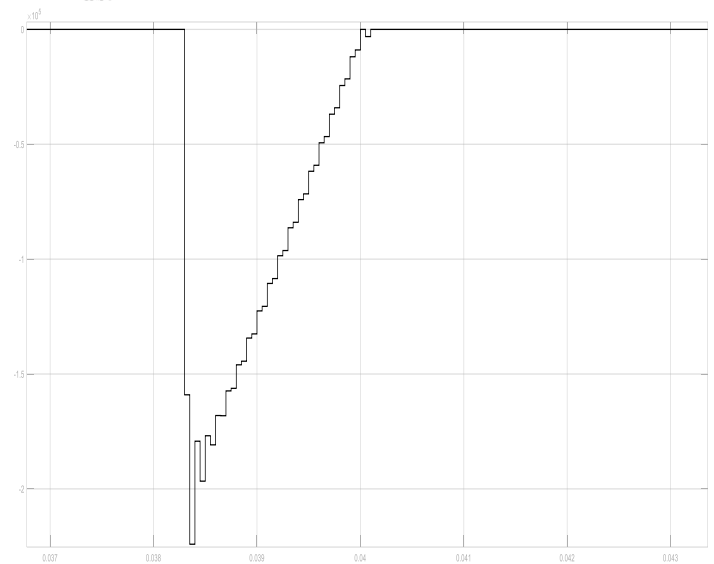


Figure(7) closer view of current waves.

AND THE VOLTAGE WAVE:

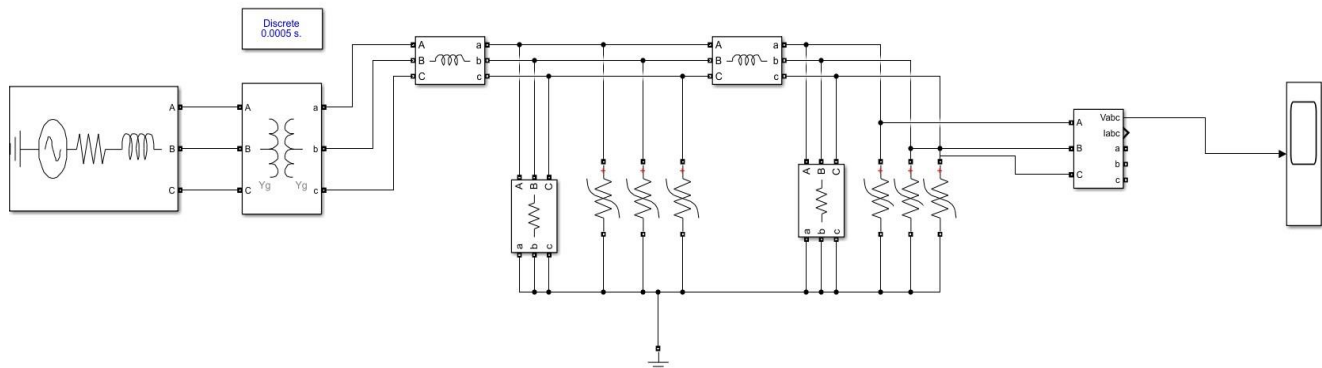


Figure(8) voltage wave



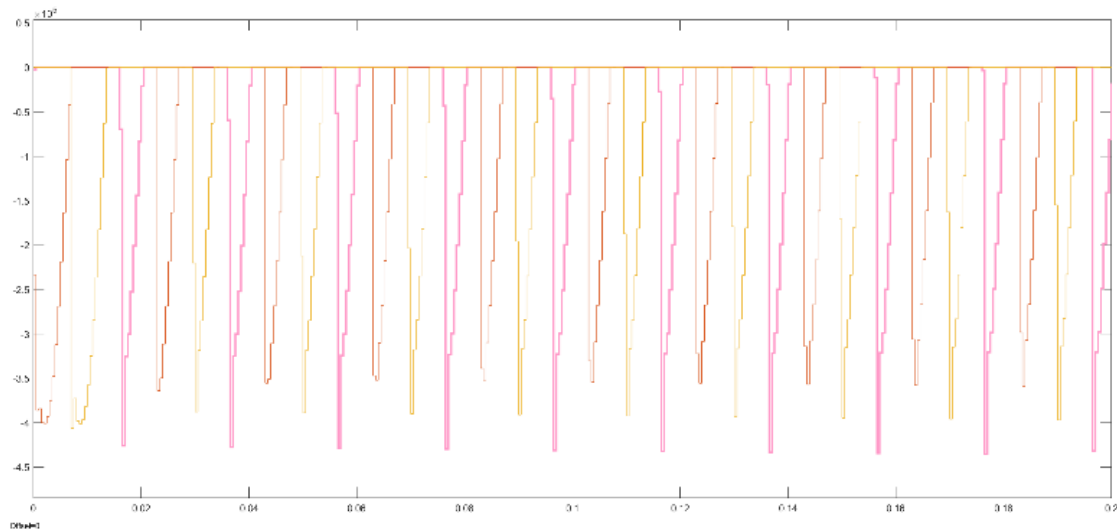
Figure(9) closer view of voltage wave

in next part, the 3 phase circuit will be analyzed.



Figure(10) 3phase lightning arrester model

the transformer is 250kva with 20/0.4kv and 50 hz frequency. the resistance and the inductor value are as the same above circuit. the main source is 25kv. 6 nonlinear resistors are exist.



Figure(11) voltage wave diagram of circuit

As shown in the pictures above, the wave exhibits disturbances and uncertainties caused by the lightning strike. Ultimately, the wave converges to the rated voltage and current levels.

Conclusion

This article discussed the types of lightning arresters and their operational mechanisms, supplemented by two MATLAB simulations (single-phase and three-phase). When lightning strikes a phase wire, it can induce transient conditions that manifest as asymmetric voltage for approximately 0.001 seconds. Once the lightning discharge subsides, the system typically resumes normal operation without any lasting disturbances.

However, if lightning strikes and connects to a surge or lightning arrester, the grounding impedance directs the surge current to the ground, effectively mitigating overcurrent situations. In scenarios where the lightning event is prolonged or more intense, it may necessitate the opening of the feeder breaker by the relays to protect the system.



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