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Frequency and Time Series Analysis of Surge Arrester in Power Distribution Systems

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Highlights

- Surge arresters protect sensitive equipment from excess voltage.
- Research focuses on FEM and heat transfer modeling to assess risks and faults.
- Temperature, electric fields, and thermal stress are key factors in performance.
- Frequency and time series analysis help in short-circuit behavior understanding.
- Enhanced design strategies ensure reliable overvoltage protection in power systems.

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Abstract

Surge arresters are essential protective devices in power systems that redirect excess voltage and prevent damage to sensitive equipment. Extensive research has been conducted in electro-thermal modeling for surge arresters to better understand and mitigate faults and accidents. These efforts have largely focused on FEM and heat transfer modeling techniques to analyze temperature distribution, electric field effects, thermal-mechanical stress, burning point analysis, puncture risks, and thermal runaway behavior. This study also presents frequency and time series analysis of surge arresters during short circuits. By integrating these two analyses, engineers can enhance their understanding of surge arrester behavior during short circuits, refine design strategies to address issues like resonance and harmonics, and ensure reliable system protection against overvoltage occurrences.

Nomenclature

Abbreviation	Definition
DC	Direct current
F	Field intensity
FEM	Finite element modeling
FRA	Frequency Response Analysis
HMSSAs	High mechanical strength surge arresters
I	Current
K	Kelvin
MCA	Multi-chamber arrester
ML	Machine learning
MOSA	Metal oxide surge arresters
MOV	Metal-oxide varistor
MV	Medium voltage
PSCAD	Power Systems Computer-Aided Design
SF6	Sulfur hexafluoride

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SPDs	Surge protection devices
SSA	Smart surge arrester
T	Temperature
V	Voltage
ZnO	Zinc Oxide

1. Introduction

Surge arresters are protective devices used in power systems to divert high-voltage surges and prevent damage to equipment. They are designed to quickly discharge excess energy safely into the ground, thereby protecting sensitive components from overvoltage conditions [1, 2]. Deficiencies in the internal components and insulation can allow moisture to penetrate more quickly into metal oxide surge arresters, increasing power loss and accelerating oxidation and aging damage [1]. The issue arises when a significant event, such as an overvoltage, causes the surge arrester to accumulate and dissipate energy, raising the temperature of the varistor by as much as 40°C [1]. Reference [3] examined various designs of metal oxide surge arresters across different frequency ranges, using PSCAD to calculate residual voltage and absorbed energy, and compared simulated outcomes with actual observed data. The properties, structure, conventional ceramic manufacturing approach, and description of ZnO varistors used in surge arresters are covered in [4]. The goal of [5] was to ensure uninterrupted operation in the event of lightning-induced overvoltages and failures in overvoltage protection, whether on the client side or in the MV network. The lack of electrothermal analysis in previous studies, including [4] on zinc oxide surge arresters, represents a research gap. Understanding the performance of these arresters under high electrical and thermal stress is crucial for optimizing their design, performance, and reliability in power systems.

Networks are impacted by lightning surges, and during large shock transients, the efficiency of MOSA is crucial [6]. While reference [6] achieved significant outcomes, a shortcoming was the lack of practical implications and recommendations for implementing lightning defense systems in distribution networks based on the simulation results. Silakhori et al. [7] conducted an electro-thermal analysis and suggested that a short-circuit current greater than 30 kA may employ an MCA. The air gap among the electrodes experiences electrical failure when a lightning impulse current is applied to the MCA, resulting in a discharge across the poles in a very small area of the chambers. The absence of empirical data limits the study's practical applicability and reliability in real-world lightning protection scenarios. Reference [8] highlighted the importance of choosing suitable arresters in distribution networks for potential breakdowns, addressing the causes of MOSA failures, and suggesting cleaning and insulation evaluation. Fu et al. [9] applied simulation and experimentation techniques to examine the current leakage of an arrester under typical working conditions and different levels of humidity. The results show that operating voltage and humidity have a major impact. The main purpose of reference [10] was the identification of MOSA fast breakdown. The study presented FRA to detect damage. However, FRA may not always be sensitive enough to detect early stages of degradation or partial faults. FRA is primarily used to identify significant changes in the mechanical structure of an arrester, but it may not be as effective in detecting minor faults or localized damage that could lead to failure over time.

Measurements of leakage current from the manufacturing and use of varistor surge arresters in the electrical industry are discussed in [11]. Although reference [12] focused on the impact of SF6 fluid flow on heat loss, it also investigated the thermal properties of a neutral bus multicolumn parallel arrester under harsh conditions. Further research may be needed to explore the impact of different operating conditions, fault types, and arrester designs on the thermal behavior of arresters to provide a more comprehensive understanding of these factors [12]. Reference [13] used a combined electrothermal computational simulation to study the thermal reliability of station-class surge arresters. It was discovered that enhanced heat transfer in the air gap raises the thermally stable limit when an ungraded 550 2kV-station design was tested. Cai et al. [14] examined the V-I curves, DC parameters, and non-linear variables at various temperatures to assess the efficiency of ZnO arresters from four manufacturers. The findings demonstrate that temperature significantly impacts ZnO arresters' effectiveness, with V-I curves lowering and turning points shifting as the temperature rises. The thermal response to commercial frequency overvoltage simulation and heat transmission in a surge arrester was evaluated in [15]. To model real-world behavior accurately, [16] used FEA to analyze the failure processes of HMSSAs under cantilever loading conditions. Small variations in parameters can lead to significantly different results, which may introduce uncertainties in the analysis. Reference [17] utilized MATLAB and ATPDraw software to assess the effectiveness of common SPDs, such as the IEEE and Pinceti models. The outcomes emphasized the importance of managing shielding in power systems, demonstrating that the IEEE scheme is more effective at lightning arresting in MV grids. Several articles have focused on modeling arresters [18–23]. The investigation of protection against surges at the low voltage level has been researched even in other articles, and software has been prepared for it [24].

The combination of frequency analysis and time series analysis allows engineers to better understand the behavior of surge arresters during short circuits, optimize their design to mitigate risks such as resonance and harmonics, and ensure reliable protection of the system against overvoltage events. Moreover, this study presents the analysis of short circuit faults and their impact on system parameters, addressing gaps identified in previous studies.

1.1. Purpose and Goals

To ensure the reliability and security of electrical networks, it is essential to thoroughly analyze arresters under fault conditions, such as short circuits in power systems. A comprehensive understanding of arrester responses during short circuits can be achieved using two types of analysis: frequency analysis and time series analysis. Frequency analysis helps identify key spectral components, which is crucial for assessing arrester performance and mitigating potential hazards. This analysis provides insights into how arresters respond to different frequencies, enabling better evaluation of their effectiveness. On the other hand, time series analysis offers a continuous perspective, allowing for the tracking of arrester responses throughout short-circuit events. This approach provides a dynamic view of how arresters perform over time, which is essential for understanding their behavior during actual faults. Combining frequency and time series analyses enhances the evaluation of arrester efficacy, providing valuable insights for strengthening system resilience and optimizing protection mechanisms. By integrating these analytical methods in the study of arresters under short-circuit faults, significant advancements in power system protection can be achieved, ultimately improving the overall efficiency and stability of the grid.

The key highlights of this study include:

a. Providing a comprehensive simulation model for arresters.

b. Examining the arrester's operation through dual analysis.

c. Implementing both frequency analysis and time series analysis in the simulation of the arrester.

d. Investigating short circuit faults to assess and enhance the performance of the arrester.

e. Examining V-I curves at various degrees.

f. Assessing this fault by analyzing various parameters such as voltage diagrams on both sides of the capacitor, bus voltage, fault current, arrester leakage current, and transformer current.

The following sections outline the simulation system in MATLAB. Section III presents the analysis of the simulated system. The discussion and future scope are shown in Section IV. Section V presents the conclusions.

2. System modeling

In this study, a 730 kV, 300 km transmission line is used to transfer power from bus B1 (equivalent to 735 kV) to bus B2 (equivalent to 315 kV). For simplicity, the simulation focuses on a segment of the entire system. To enhance transmission capability, the line is equipped with a capacitor at the center that compensates for 40% of the line's reactive power.

Additionally, the line is compensated on both sides by a 330 MVAR (110 MVAR/phase) shunt regulator. As illustrated in Figure 1, the series capacitance is protected by a Metal-Oxide Varistor (MOV), simulated by an explosive block. The 250 MW, 735 kV/315 kW transformer is represented by a filler transformer block simulating a 750 MW 3-phase transformer block. Measurements are used to monitor the spark current and the magnetic transformer current. All these components are depicted in Figure 1. Furthermore, Figure 2 highlights the importance of surge arresters in power systems.

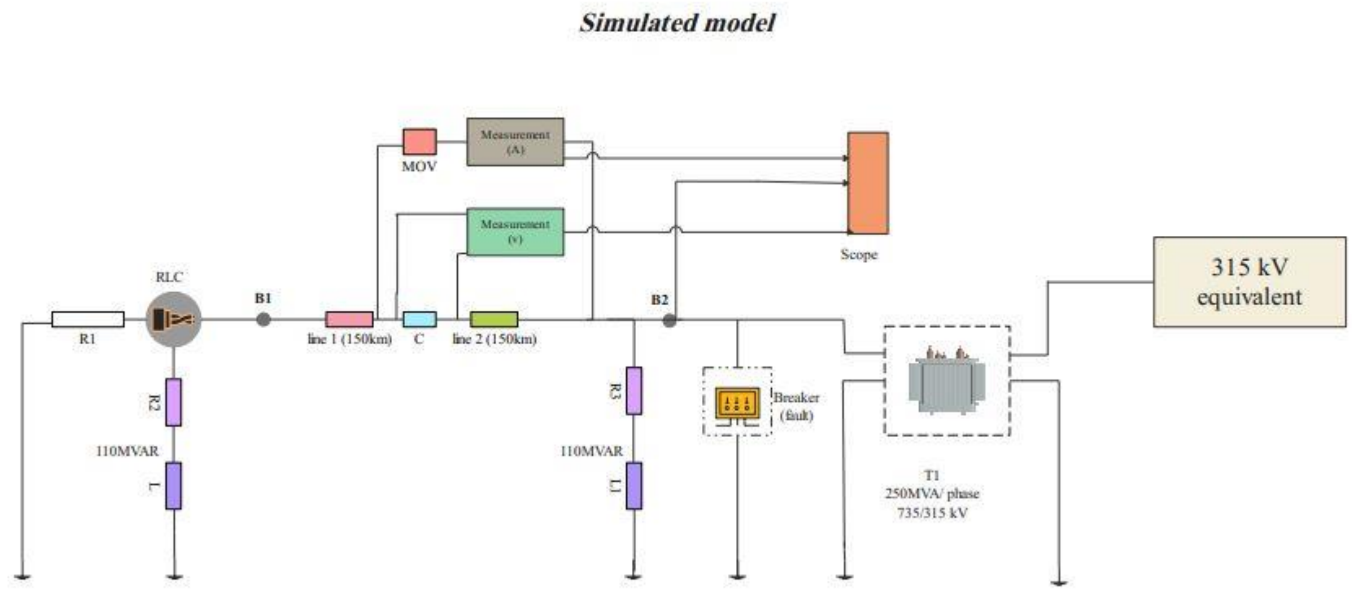


Fig. 1. Simulated model in MATLAB/Simulink

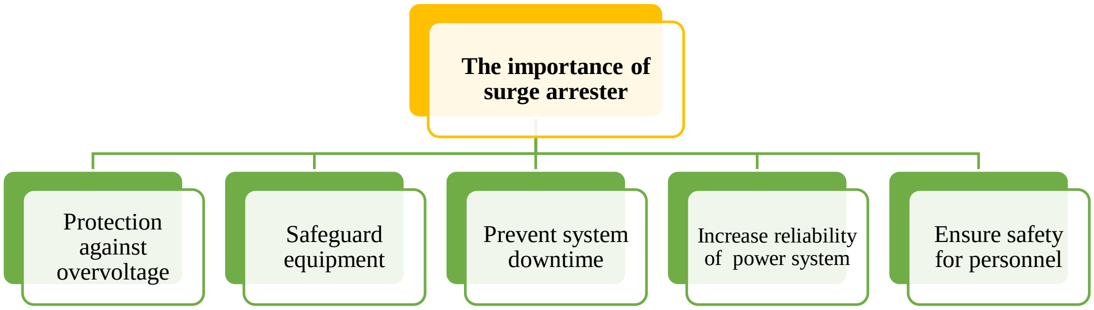


Fig. 2. The important role of surge arresters

The leakage current of the surge arrester at nominal voltage is a function of the temperature and the intensity of the applied field. In the simulation, the leakage current model of the surge arrester is defined using equation (1) [25] as follows:

$$J(F) = 2 * F\left(2A_1 + A_2\, exp(\frac{a_1}{T}) \times \left[1 - tanh(a_2 + \frac{a_3}{T} - \frac{a_4}{F}\right]\right)^{-1} \quad (1)$$

Table 1. Parameters up to equation (1).

Parameters	Fixed Value
A1	1
A2	0.70
a1	8000
a2	13
a3	4004
a4	38235

In equation (1), the current density is represented in A/cm², and the voltage gradient (F) is in V/cm. Figure 3 shows the voltage of the surge arrester at different temperatures. Tables 1 and 2 present the parameters used for the simulation in MATLAB.

Table 2. Following parameters in MATLAB coding.

Parameters	Value
T	293:40:493 (40 is step stage is MATLAB code)
F	1870 (V/cm)

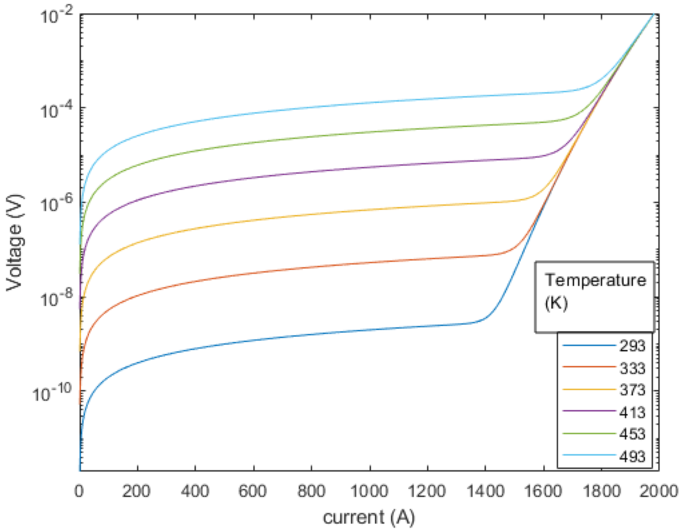


Fig. 1. V-I characteristics of the surge arrester for different temperatures

Figure 3 illustrates the V-I characteristics of the surge arrester at different temperatures. Figure 1 demonstrates how the arrester's ability to transmit and release energy can change with temperature variations. At lower temperatures, increased resistivity can reduce the arrester's effectiveness in clamping voltage. Conversely, higher temperatures can lower the clamping voltage by increasing the conductivity of the arrester's components, which may lead to excessive clamping voltages and diminished protective efficacy. However, prolonged exposure to high temperatures can also cause thermal aging, potentially shortening the arrester's lifespan.

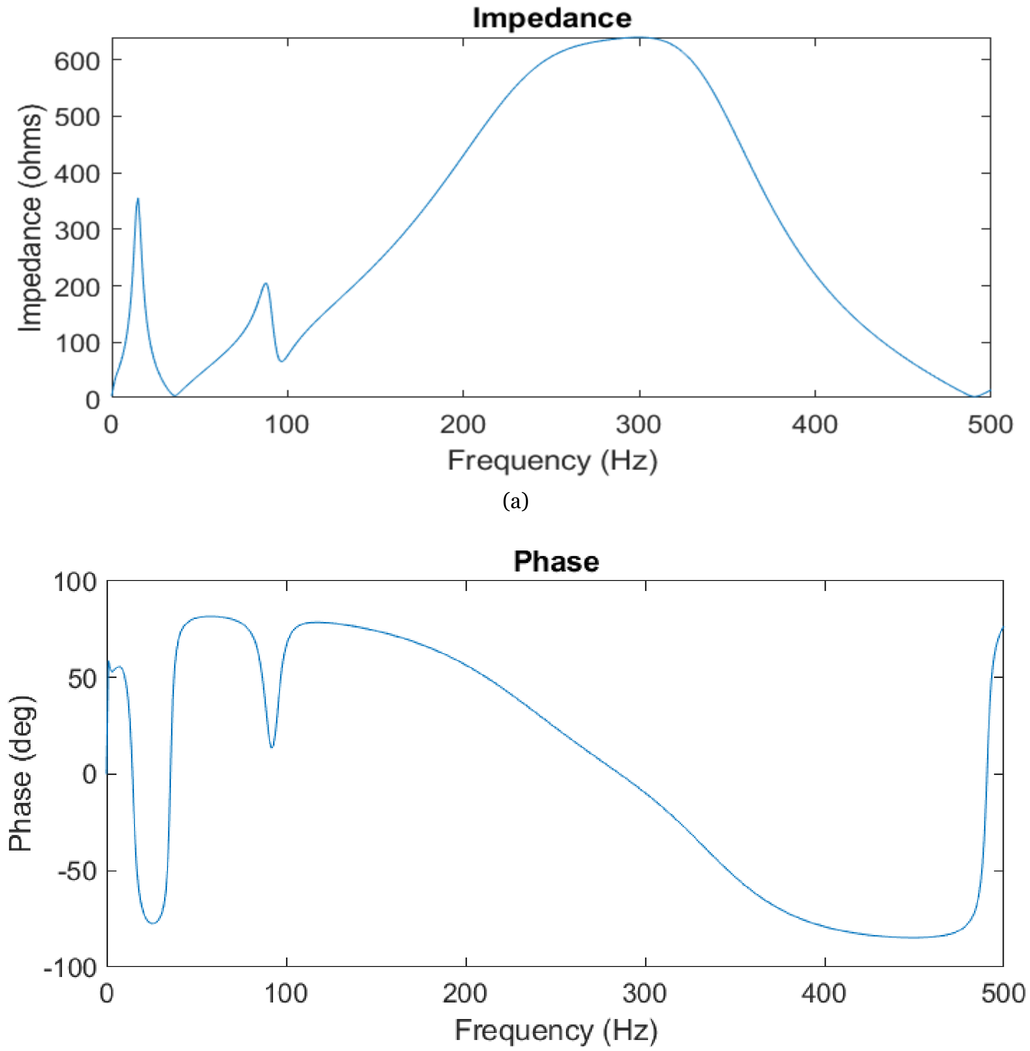
The following sections will examine the transient performance of this circuit under a 6-cycle short circuit fault applied to the B2 node. The fault is simulated using a breaker block, with the switching times set in the breaker block (closing at t = 3 cycles and opening at t = 9 cycles). The next section presents two analyses of the arrester's performance.

The relationship between voltage (V) and current (I) for a component at various temperatures, ranging from 293 K to 493 K, is depicted in the provided graph. The vertical axis represents voltage on an exponential scale, while the horizontal axis shows current on a linear scale. This graph illustrates that temperature significantly affects the electrical properties of the material or device, particularly the current-voltage relationship. This effect is typical for temperature-sensitive materials, such as semiconductors, where thermal energy alters electrical characteristics and impacts the material's performance.

3. Analysis and evaluation

3.1.Frequency analysis

This analysis involves measuring the impedance at the B2 node using an impedance measurement block connected to node B2, as shown in Figure 4. The analysis covers the 0-500 Hz frequency range. The impedance curves obtained reveal two primary parallel resonances: one at 15 Hz and another at 300 Hz. The 15 Hz resonance results from the parallel resonance of the series and dual reactive capacities, while the 300 Hz resonance is primarily due to the shunt line capacitor and the series regulator in the transmission system. These resonances can be activated during fault conditions, influencing the operation of the circuit. Understanding these behaviors is crucial for ensuring the surge arrester's efficiency in protecting the power system. Figure 4 illustrates the frequency analysis with (a) the system's equivalent impedance plotted against frequency, and (b) the phase plotted against frequency, as observed from bus B2.



(a)

(b)

Fig. 4. Frequency analysis diagram showing (a) the system's equivalent impedance versus frequency and (b) phase versus frequency from the perspective of bus 2.

The impedance is quite high at low frequencies and shows a noticeable peak around 50 Hz, indicating possible resonance or a strong reactive component at this point. As the frequency goes up, the impedance varies, with another significant peak around 350 Hz, reaching a maximum of over 600 ohms before it starts to decrease.

There's also a large phase shift near 0 Hz, almost reaching 90 degrees, which then changes as the frequency increases. These shifts indicate variations in the surge arrester's reactive properties.

Finding these resonance frequencies is crucial because they can cause the system to overwork and potentially fail. At these points, the system might amplify certain frequencies, which can be damaging. Understanding the phase response is also important as it reveals the timing differences between voltage and current, which is essential for designing surge protection that works well against sudden spikes. By examining both impedance and phase across different frequencies, engineers can ensure the surge arrester functions effectively, protecting electrical systems from unexpected surges and transients.

3.2. Time Series Analysis

System analysis of a short circuit fault at Bus 2 is conducted to evaluate the performance of the surge arrester. At time t = 3, a single-phase short circuit fault is applied to the ground, causing the fault current to reach 10 kA, as shown in Figure 5-1. During the fault, the surge arrester is engaged in each fault cycle, limiting the capacitor's overvoltage, which is depicted in Figure 5-2. The capacitor voltage is constrained to 263 kV. The short-circuit fault is then cleared at t = 9 cycles, as defined in the block in Simulink. This can be observed in Figure 5-3. The total simulation time is 0.4 s in MATLAB/Simulink.

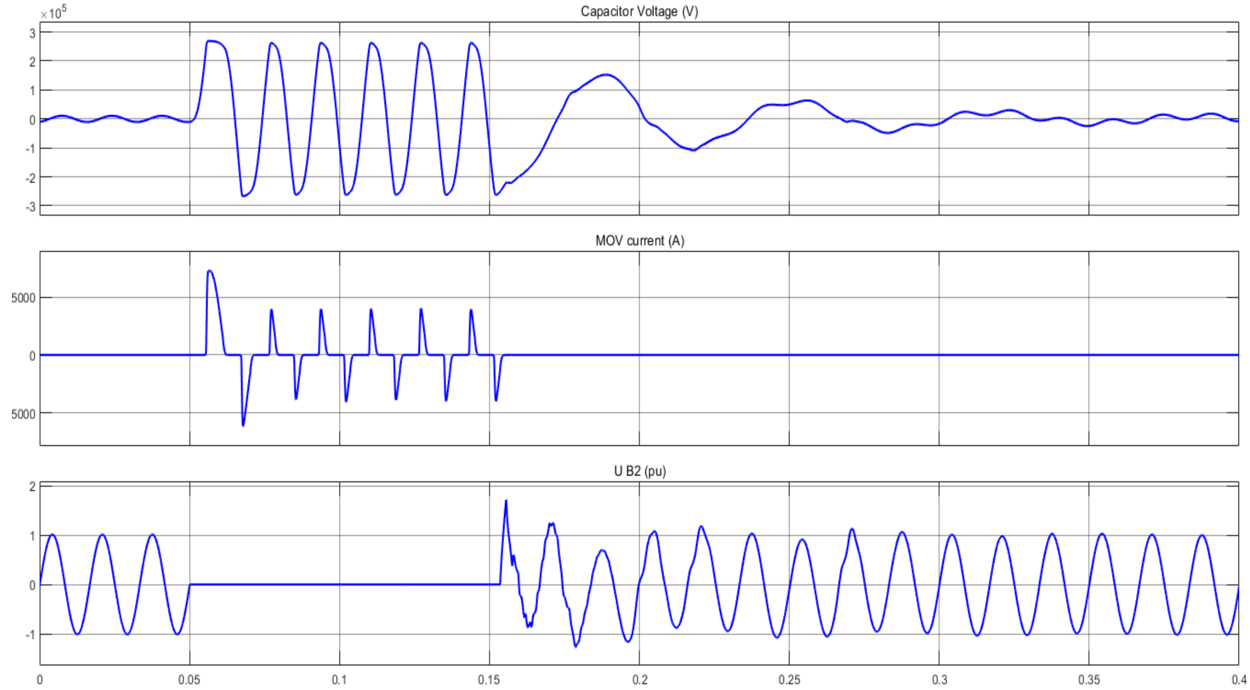


Fig. 2. Voltage diagrams showing (1) both sides of the capacitor, (2) the surge arrester, and (3) the voltage at bus 2.

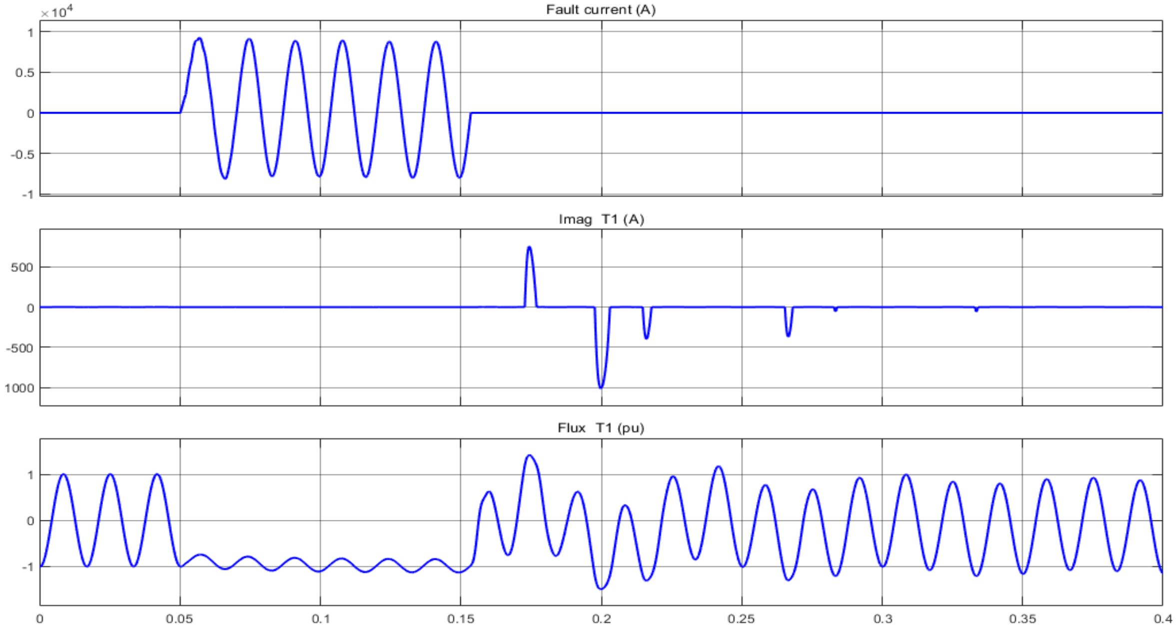


Fig. 6. Fault current (1), surge arrester leakage current (2), and transformer current (3).

The 15 Hz resonance frequency is observed in both the capacitor voltage and the B2 bus voltage. During the post-fault period, the transformer flux remains at 1 PU, thanks to the timely and effective operation of the surge arrester, which prevents the transformer from becoming saturated by inrush current once the turbulence is resolved. This is illustrated by the fault current in Figure 6-1, where the fault current is zero due to the surge arrester's prompt action. Additionally, figures 6-2 and 6-3 show the transformer's saturation current and the surge arrester's magnetic leakage current, respectively, caused by the voltage rise in the capacitor, which leads to the transformer's saturation.

4. Discussion and Future Scope

Surge arresters are critical components in electrical systems, protecting against sudden high voltages caused by fault conditions, switching operations, and lightning strikes. Time series analysis and frequency evaluation are essential methods for understanding and enhancing the efficiency of surge arresters. Surge arresters must function effectively across a broad frequency range, as over-voltage phenomena can occur in various forms.

Frequency analysis techniques are valuable for understanding how surge arresters respond to different frequency components of transient events. Since the protective characteristics and impedance of arresters vary with frequency, studying their frequency behavior allows engineers to design arresters that offer optimal protection across the expected range of transient frequencies.

Time series monitoring involves evaluating the arrester's performance over time and under varying conditions. This analysis identifies trends, cycles, and anomalies in surge arrester operation using data such as voltage and current curves recorded during surge events. This information is crucial for assessing the arrester's effectiveness, diagnosing potential issues, and improving its design and maintenance procedures.

Severe over-voltage and over-current conditions, such as those caused by short circuits, can impact surge arrester performance. During a short circuit, the arrester must quickly clamp the voltage to protect all system components. The heat and electrical stresses from such events can weaken the arrester material, affecting its long-term reliability and performance. By examining arrester performance under short circuit conditions, engineers can better understand the impact of temperature, as surge arrester materials are sensitive to temperature changes, which affects their voltage-current (V-I) properties.

Further investigation is needed in the field of surge arrester analysis, encompassing various potential future directions, as illustrated in Figure 7. The processes and objectives required to achieve the desired outcomes are detailed in Figure 8.

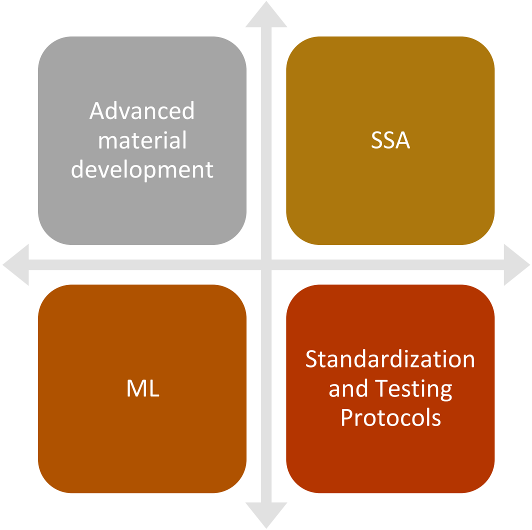


Fig. 7. Suggested areas for future research in surge arrester studies

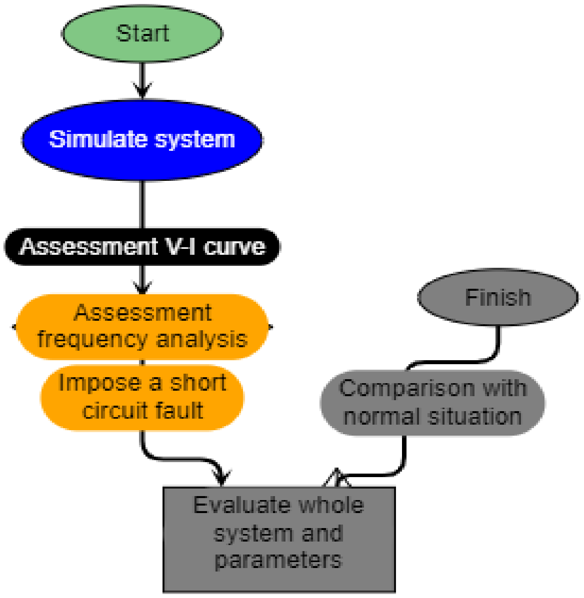


Fig. 3. The procedures and objectives that will be followed to attain the desired result

5. Conclusion

In summary, operating a distribution system without lightning protection significantly jeopardizes the system's security and performance. Without adequate protection, loads and system components are exposed to high overvoltage conditions, which can cause equipment failures and insulation breakdowns due to lightning strikes. Implementing protective devices, such as surge arresters, is essential for mitigating these risks. Surge arresters can be employed in various configurations to protect the system.

This study focuses on system simulation and the assessment of the V-I curve across different temperatures. It evaluates two types of analysis: frequency and time series. Additionally, the study aims to simulate short circuits to assess the performance of surge arresters and evaluate the impact of such faults on parameters such as voltage diagrams on both sides of the capacitor, bus voltage, fault current, arrester leakage current, and transformer current. The system simulation was conducted using Simulink, while the V-I curve was generated through MATLAB coding.

Competing Interests:

The authors declare no competing interests.

Author Contributions Statement:

Alireza Zabihi, conceptualization, investigation, computations, and writing the original draft, and Mohammad Parhamfar contributed to conceptualization, supervision, manuscript improvement, and editing. All authors have read and approved the final version of the manuscript

Data Availability Statement:

The article contains the original contributions made in the study; additional questions should be forwarded to the relevant authors.

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Not applicable.

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All authors have been personally and actively involved in substantial work leading to the paper and will take public responsibility for its content.

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