

# Adaptive Control Mechanisms for Real-Time Performance Optimization of Lightning Arresters

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## Abstract:

The creation of adaptive control techniques to maximize lightning arresters' real-time performance is investigated in this study. Building a strong framework for the real-time collection of environmental and operational parameter data, developing a dynamic control algorithm that modifies settings according to the situation, modeling the adaptive system's performance in various environmental scenarios, and verifying the benefits over traditional fixed systems are the main goals. The study shows that adaptive systems greatly improve performance, attaining greater responsiveness and dependability than conventional techniques, using a combination of data-driven analysis and simulation. A strong argument for switching from fixed to adaptive mechanisms in lightning-related risk mitigation is made by the results, which show that applying adaptive control strategies in lightning arrester management can enhance electrical system safety and efficiency.

Keywords Used- Adaptive Control, Lightning Arresters, Real-Time Performance Optimization, Environmental Parameters and Dynamic Control Algorithm

## Introduction

Regarding distribution networks lightning is one of the most common factors that lead to power outages. Surges caused by lightning could cause significant damage to the equipment in distribution networks that are located underground as well as overhead [1]. Lightning could have a huge and frequent impact in areas with high ground flashing density. Ground flashing density is a measurement of lightning activity that is often represented as the number of flashes that occur per square kilometer in a given year. Depending on the geographic location of the lightning hit the lightning events could be either direct or indirect [2]. When lightning strikes directly on any conductors or electronics of an overhead electrical line, this is known as direct lightning discharge. The immense energy that is produced by the current produced by a lightning bolt could fail equipment, melt or burning of components, and even damage to the structure by itself. When lightning strikes the ground or an item nearby, it is referred to as indirect lightning. The creation of a rush of electrical energy characterizes this

type of lighting [3]. The surge could cause a high voltage to be induced in the distribution line. This high voltage could then move along through the conductors and destroy delicate devices, such as transformers, breaker panels, and other electrical components that are linked to the distribution network.

Therefore, protective measures, including lightning arresters, grounded systems, thus surge protection devices, are essential to limit the potential damage that could be caused by lightning strikes and to ensure the durability of distribution networks [4]. This is true regardless of the type of lighting that is based on its location. When compared with direct lightning strikes, indirect lightning incidents take place in distribution lines at a greater frequency than direct lightning strikes.

When it comes to building efficient protection methods for distribution lines, it is essential to acknowledge the greater occurrence amount of indirect lightning [5]. This is because it helps to limit the dangers connected with the situation and ensures a stable supply of electricity. The voltages that are induced on lines for distribution by lightning that is emitted indirectly are lower than 300 kV. It is not necessary to be concerned about induced flashovers when dealing with lines that have critical flashover voltages (CFO) that are larger than 300 kV [6]. However, when dealing with lines that have lower CFO values, the voltages that are induced have a greater influence. To protect electrical systems from high-voltage surges that are induced by lightning, lightning arresters are units that are installed in the transmission and distribution networks. These devices are responsible for directing the extra voltage to the ground, and so preventing damage to transformers, breakers for circuits, and other critical pieces of infrastructure [7].

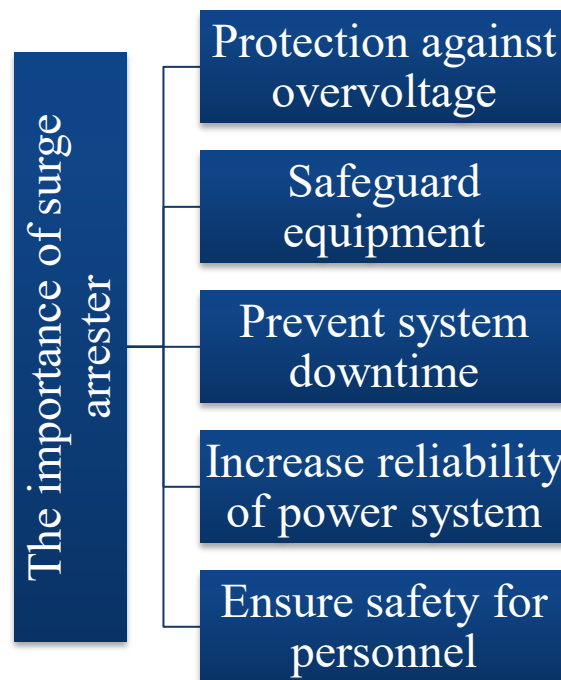
Lightning could cause significant damage to distribution networks, and there have been many potential measures proposed to mitigate this harm. These options include the installation of surge Arrestors (SAs), lightning rods, as well as shield wires (SW), which include both overhead grounding wire (OHGW) as well as underbuilt shielding wire [8]. By taking these precautions, lightning strikes could be redirected away from vital pieces of equipment, hence lowering the likelihood of power outages occurring. Lightning could have a significant influence on distribution networks, and utilities could increase the dependability of their systems and minimize the impact that outages have on their consumers if they understand the impact that lightning has on distribution centers and apply suitable solutions.

### **1.1 Surge Arresters**

To prevent overvoltages, surge arresters, also known as SAs, are protective devices that are utilized in substations. The basic thunderbolt impulse insulating level (BIL) could be exceeded by the stochastic resistance feature of SAs, which protects equipment against overvoltages [9]. The amount of voltage at the device terminals is impacted by the positions of SAs [10]. There are several highly essential aspects to consider, including the desirable stability of UHV substations, the coordination of insulators, and the determination of the optimal distance between SAs to safeguard the equipment. There are several benefits

associated with SAs, including their ability to respond quickly to overvoltages, their excellent reliability, their minimal losses, and their proper nonlinear behavior [11].

The overvoltages caused by lightning back flashover (BF) on the electrical cables that are linked to the substations are the primary cause of power outages in ultra-high voltage (UHV) substations [12]. Deployment of SA in the system is a simpler alternative to reducing the tower's footing resistance, and it is also an alternative to avoiding shielding failure. Metal oxide varistor (MOV) type surge arresters are the most prevalent type of surge arrester [13]. These surge arresters are gapless and are referred to as non-gapped line arresters (NGLA). These surge arresters are an updated device in comparison to gapped silicon carbide arresters. The MOV robust type SA is utilized in the transformers as well as riser poles of the distribution power lines [14]. The use of externally gapped line arresters, also known as EGLAs, is a cutting-edge and forward-thinking method for minimizing the consequences of lightning-induced high voltages on horizontal distribution networks and towers/poles. The line arrester is typically installed in areas with a high ground flash density; however, due to financial constraints, it is not required to be installed in all distribution towers [15]. After taking into account the technological, economic, and atmospheric requirements, several researchers concentrated their efforts on locating SAs in a single phase or in a smaller number that covered the complete network. In this particular scenario, it is anticipated that the system will be able to function efficiently at a restricted number of SAs without sacrificing its intended purpose [16].



**Figure 1: Role of surge arresters [17]**

The surge arrester is a safety measure that is utilized to safeguard electrical equipment from harm that could be caused by lightning surges or various transients that occur within electrical power systems [18]. A surge arrester is a device that creates a low-impedance

conduct for the surge energy to pass to the ground in the event of lightning surges. This allows the surge energy to flow to the ground, so lowering the voltage that is applied to the protected equipment as well as preventing damage [19].

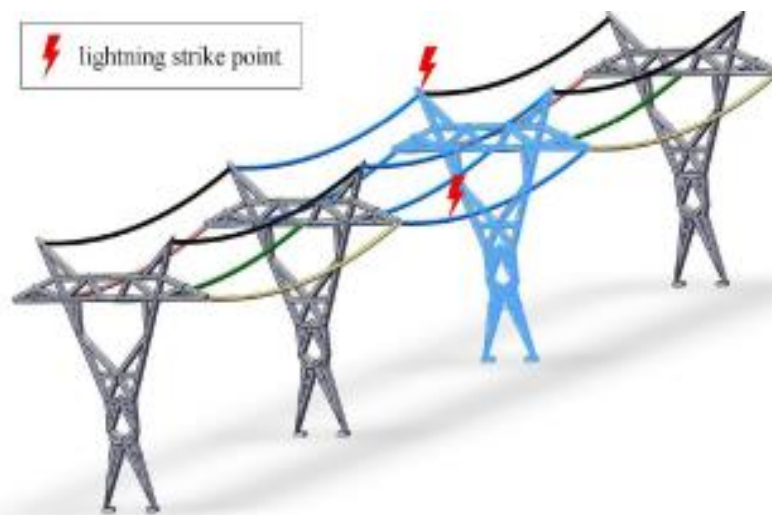
Surge arresters are made out of a nonlinear resistance such as an iron oxide varistor that is linked in series with the equipment that is being protected and has a path to ground that has a low impedance [20]. Whenever a lightning surge or another type of temporal occurs, the voltage over the surge arrester is higher than its breakover voltage. This causes the nonlinear resistor to conduct the surge current, which causes the surge to be accelerated. Different kinds of surge arresters are available for use in a variety of applications. These surge arresters include low-voltage arresters, distributing arresters, and overhead line arresters [21].

### **1.2 Challenges in Current Lightning Arrester Performance**

- **Varying Environmental Conditions:** Changes in temperature, humidity, and air pressure could impact arrester efficiency.
- **Aging and Degradation:** Over time, arresters could degrade, reducing their ability to respond to surges.
- **Fixed Design Parameters:** Traditional designs rely on fixed operational thresholds that do not adapt to real-time conditions, potentially leading to either overprotection causing unnecessary stress on the system, or under protection resulting in system damage [22].

### **1.3 Lightning strike**

The accumulation of electrical charges in thunderstorms is the cause of lightning strikes, which are quick and strong discharges of energy from the surrounding air to the earth or another object [23]. Lightning strikes could be triggered by lightning strikes. Lightning strikes have the potential to cause major damage to electrical systems and infrastructure, and they also pose a significant risk to both people and animals [24]. It is believed that the accumulation of electrical charges in thunderstorms is the phenomenon that causes lightning, even though lightning is a complicated phenomenon that is not yet completely understood [25]. The lightning strike that results from this could transport numerous thousands of half amperes of current toward the ground in a tiny fraction of a second, so producing an electrical surge that is both high-voltage and high-frequency [26]. The intensity of the lightning strike and the distance between the strike with the target both have a role in determining the consequences that could be caused by lightning strikes. As an illustration, a lightning strike that is directly directed at a structure could result in a fire, an explosion, or structural damage. On the other hand, a lightning strike that is located nearby could result in EMI, electromagnetic interference, and electrical surges, all of which could cause damage to delicate electronic devices [27]. A recent study has been released that reveals the detection of lightning has come owing to space-based operational lightning images [28]. This decision was made in light of the potentially catastrophic repercussions that lightning strikes could have on both people and their property.



**Figure 2: Schematic Diagram of Tower [29]**

#### **1.4 Impact of changing environmental and electrical conditions on arrester effectiveness**

The electrical properties of high-voltage insulators are diminished when they are subjected to environmental conditions such as high temperatures, and precipitation including snow, rain, salt, and dust [30]. Lightning arresters are critical components in safeguarding electrical systems from transient overvoltage caused by lightning strikes or switching surges. However, the effectiveness of these arresters could be significantly influenced by both environmental and electrical conditions.

- **Temperature Variations:** Lightning arresters could experience changes in their insulating and conduction properties due to temperature fluctuations. High temperatures could degrade arrester materials, reducing their ability to discharge overvoltages effectively [31].
- **Humidity and Moisture:** High humidity levels or moisture infiltration could lead to surface contamination and reduce insulation resistance. This could result in increased leakage currents, potentially compromising the arrester's performance.
- **Pollution and Contamination:** Environmental pollutants, such as dust, chemicals, or salt, could accumulate on the surface of arresters, leading to flashovers and decreased dielectric strength. This contamination could further affect the arrester's capability to handle surges.
- **Electrical Load Fluctuations:** Electrical systems could experience load variations, which could affect the voltage across the arrester. A high or low load could lead to different stress levels on the arrester, influencing its energy absorption and discharge capabilities.
- **Voltage Transients:** Variations in the system voltage due to switching surges or lightning strikes could also affect the arrester's effectiveness. The arrester must react quickly and efficiently to overvoltages, otherwise, it risks malfunctioning, leading to damage to the protected equipment [32].

- **Aging and Degradation:** Over time, the materials and components of lightning arresters degrade due to repeated exposure to environmental and electrical stressors. This gradual deterioration reduces the arrester's ability to respond to overvoltages, compromising overall system protection.

#### 1.4.1 Rain effect

When it comes to power frequency and switching impulses, rain has a highly significant impact on lowering the disruptive discharge voltage, although lightning impulses only see a slight reduction [33]. To determine the power frequency and switching impulse values for exterior insulation, wet experiments are conducted. On the other hand, dry tests are the only ones that are conducted for lightning impulses [34]. However, the efficiency of rain in cleaning the bottom surface of insulators varies depending on the strength and quantity of the rain [35]. Rain is particularly successful at washing the upward-facing surface of insulators. Under wet conditions, the DC breakup strength of insulators could be significantly lower than the maximum measured flashover gradients of 400 kV/m for both polarities of insulators under dry conditions. This is the case regardless of the polarity of the insulator. When it rains, the negative polarity flashover, which could range from 170 to 400 kV/m, is often lower than the positive polarity flashover, which could range from 300 to 500 kV/m. This difference is contingent upon the type and orientation of the insulator, as well as the rain conductivity, intensity, alongside duration. For the ratio between the wet and the dry as a flashover of insulator strings, the Working Group on Issue 33.07 proposed a factor of  $0.87 \pm 0.12$  as the optimal value. In the case of longer string lengths, the ratio of dry to wet lightning flashover that is determined by the IEC wet test is approximately 0.7, which is generally consistent overall [36].

#### 1.4.2 Icing effect

Several factors, such as the arrangement of the electrical field, the level of wetness and contamination of the ice surface, the amount and location of air gaps created by ice icicles within the insulating chains, the surroundings, and the form and size of the layer of ice on the insulation, all play a role in determining the impact that ice accretion has on the strength of the insulation and the flashover voltage [37]. Insulators are designed to not only offer appropriate clearance among parts at different potentials but also to generate the maximum creepage separation for the flow of the lowest leakage current. This is done under standard environmental circumstances. Insulators are designed to provide both of these benefits [38].

### 1.5 Need for Real-Time Performance Optimization

To ensure reliable protection of power systems, there is a growing need for lightning arresters that could adapt their performance based on real-time data.

- **Improve Response Accuracy:** Adjusting parameters in real-time allows the arrester to respond more accurately to the current conditions.
- **Extend Device Lifespan:** Adaptive control could reduce unnecessary stress on the arrester, enhancing its durability [39].

- **Reduce Maintenance Costs:** Continuous self-optimization minimizes the need for frequent manual interventions or replacements.

### 1.6 Adaptive Control Mechanisms

Adaptive control mechanisms offer a promising solution for enhancing the performance of lightning arresters. These mechanisms involve the use of advanced control systems that can monitor, assess, and adjust the arrester's performance in real-time [40]. Adaptive control integrates sensors that track key parameters such as temperature, voltage levels, and arrester health status. The control system uses this data to make adjustments in real time, either by altering the configuration or optimizing the energy dissipation process to improve the efficiency of lightning protection.

#### 1.6.1 Components of an Adaptive Control System

An adaptive control system for lightning arresters typically consists of several key components:

- **Sensors:** These continuously monitor the external environment and arrester conditions, such as ambient temperature, voltage surges, humidity, and internal resistance of the arrester [41].
- **Control Algorithms:** These algorithms process the data received from the sensors and determine the necessary adjustments to optimize the arrester's performance. They could predict failures, detect anomalies, and make real-time decisions based on the arrester's operational state.
- **Actuators:** These are used to implement the adjustments suggested by the control algorithms, making changes to the arrester's settings or operational parameters to maximize efficiency.
- **Feedback Loops:** The system operates using a continuous feedback loop, where the performance is constantly evaluated, and adjustments are made as needed to ensure optimal operation.

#### 1.6.2 Benefits of Adaptive Control for Lightning Arresters

Implementing adaptive control mechanisms provides several advantages for the real-time optimization of lightning arresters:

- **Improved Performance:** By constantly adapting to changes in the environment and electrical system, adaptive control ensures that the arrester functions at its best, even in challenging conditions.
- **Extended Lifespan:** Regular monitoring and adjustments reduce the stress on the arrester, potentially extending its service life by preventing premature failure [42].
- **Reduced Maintenance Costs:** Since the system could detect potential issues early and optimize performance, it minimizes the need for frequent manual inspections and repairs.
- **Enhanced System Protection:** With real-time adjustments, the arrester could react more effectively to high-energy lightning surges, providing better protection for critical infrastructure.

## 1. Literature Review

These are some literature reviews listed below:

**Boumous Samira, et al. [2024] [43]** proposed elements that connect loads to the power plants through transmission lines. They might bury cables underground or hang them from the ceiling. A new established technology will replace these transmission lines with subterranean gas-insulated lines (GIL). The most recent technology offers several advantages over more traditional transmission methods like hidden cables and overhead transmission lines, including low transmission losses, lower capacitive load, reliability, security for individuals, identical functioning as overhead lines, and negligible electrical aging. Due to the huge conductive surface that GIL possesses, it can handle considerably more electricity than overhead lines. When it comes to high voltage, GIL dominates. This study provided a simulation of lightning impacts on a 400 kV hybrid power line located in northeastern Algeria. This study presents the simulation with and without GIL arresters. The findings of this study have the potential to serve as a rich and relevant theoretical reference for GIL simulation modeling and the evaluation of the impact of lightning strikes on hybrids over GIL lines.

**Liu Siyuan, et al. [2024] [44]** examined the spiral design of a gas-insulated switchboard (GIS) parallel arrester with a voltage of  $\pm 550$  kV DC and found out how it affects the features of the current distribution. Through the utilization of multi-physics field simulations, this research endeavored to create a model of a 550 kV DC GIS arrester. With the use of simulations, this research endeavor determines the self-generated inductance that is present in the spiral shape of ZnO varistors. During the process of energy absorption, more research was being conducted to explore the impact that the self-generated inductance has on the present arrangement of the multi-column arrester. According to the findings, the self-generated capacitance of the spiral shape has the potential to provide a reduction in the current variation factor of between 28 and 65 percent.

**Asadi, et al. [2024] [45]** proposed to design a technique for the optimal positioning of arresters a multi-objective variable that incorporates technical, security, and risk, alongside economic indicators. The proposed model was evaluated in comparison to the models developed by the arresting model and is incorporated into an optimization problem that takes into consideration the efficiency of the over-voltage safeguard as well as the risk, scientific, and economical indices. The issue is solved by employing the techniques of particle swarm optimization (PSO) as well as Monte Carlo optimization (MC). It is necessary to simulate actual information collected, to validate the proposed arrester models and the placement technique. The feeder has been expanded to cover three distinct geographical zones, namely mountainous regions, agricultural plains, and rural areas.

**Ticoh Janne deivy, et al. [2023] [46]** suggested a common occurrence throughout the procedure of distributing power from the station to the customers by two elements: internal variables and external ones. The electrical wiring at the station is responsible for this interference. External factors include mistakes made by humans and natural disasters such as

lightning, flooding, quakes, wind, and others. Internal factors include things like a lack of appropriate equipment, whereas external causes include things like human error. The electrical equipment at the Pandu substation is equipped with a safety protection system. To limit switching high voltages and lightning bolts, followed by overvoltages by lightning current to ground, surge arresters serve a crucial function in Pandu substations. They are responsible for preventing lightning strikes. The protection effectiveness of the arrester is determined by the distance between its location and the protected equipment. The biggest system voltage that could be achieved is 165 kilovolts, the rated voltage of the arrester is 132 kilovolts, the line impedance/conductor is 475,764 ohms, the air insulating breakdown voltage is 1515.8 kilovolts, the arrester discharge current is 4.27 kiloamperes, and the ideal distance between the arrester and the transformer is 10.96 meters.

**Li Hao, et al. [2023] [47]** determined the protective concept for the air-blown interrupter gaps, and then the action process was simulated using the COMSOL Multiphysics modeling software. Constructing a frequency rejuvenation test circuit for the test is the next step in testing. A lightning trip rate calculations model and an arc-building rates calculation model are then built under the circumstance of an air-blown interrupting gap. Finally, a 10 kV aerial line in Yunnan is chosen for the verification process of the calculation example. Both of these models are established under the situation of an air-blown interruption gap. The findings indicate that a gas-blown arc gap could be completely extinguished in approximately 2.5 milliseconds of frequency arc, and no re-ignition event occurs simultaneously. After the gas blasting arc gap line was installed, the arc rate went from 37.27% and 4.1%, and the average lightning trip rate went from 8.64 times/(40 storm days—100 kilometers) to 0.333 times/(40 storm days—100 km), correspondingly. Both of these changes occurred before and after the setting up of the gap line. The rate of decrease was greater than 95 percent, and in real-life use, it was able to lower the electromagnetic trip rate to a sufficient degree to achieve satisfactory outcomes.

**Cao Jinxin, et al. (2023) [48]** investigated the lightning behavior of a 10-kV aerial distribution line that is equipped with grounded counterpoise wires. For the lightning surge study, a partial element analog circuit model is utilized, with the lossy ground being taken into consideration on the circuit. To properly evaluate the flashover rate, the Monte Carlo approach, which takes into account the randomness of natural lightning, is utilized. It has been discovered that the simple horizontal grounding rod is not successful in lightning protection when the soil conductivity is extremely low. On the other hand, the performance of the rod is greatly increased when extended counterpoise wires are used. When it comes to performance, the single-row counterpoise cable having a line span is the most effective. One of the competitive wires is the single-row counterpoise cable that has a half-length of line span.

**Zhao Amedeo Andreotti, et Al. [2022] [49]** Proposed a novel method for creating differential protection against lightning. In this study, indices are introduced that are based on the number of flashovers that occur at individual poles and are related to possible stroke locations. This is in contrast to the conventional flashover rate for a whole line. A selection

strategy could be used to identify a differentiated config of SAs depending on these flashover indices through the use of the selection strategy. Obtaining an individual SA protection scheme, which is provided by a pre-set number of SAs, is possible once numerous rounds of selection have been completed. A strategy that is based on probability and is simplified is proposed in this procedure to determine the flashover indices. The classic Monte Carlo method could be compared to this strategy, which has the potential to produce a tenfold gain in computer efficiency while maintaining a fair level of accuracy. Within the scope of this work, two distinct selection procedures are presented. When compared to the selection approach that makes use of flashover indices at particular poles, a method of selection that is based on an ensemble of poles is suggested. This is because it produces a configuration that has superior lightning performance while maintaining the same number of SAs. The application of this design technique is made to practical distribution lines that contain shield wire and structures in the surrounding area. The impact of grounding impedance, the shield wire, and structures in the immediate vicinity are taken into consideration.

**Cao Jinxin, et al. [2022] [50]** Analyzed the damage rate of surge protectors (SAs) in a network, and a novel surrogate model has been presented. The first thing that is shown is the distribution characteristics of energy absorbed into the SAs. This is based on a numerical Monte Carlo (MC) evaluation for random positions of restricted SAs in the distribution system. The energy that is absorbed into a SA is observed to generally exhibit a log-normal distribution. When this is done, it is discovered that the average values of the energy that passes into each SA decrease at an exponential rate with the length of time from the point of the direct stroke on the power lines. **Lu, Yang, et al. [2022] [51]** Analyzed the lightning present attenuation mechanism, the lightning discharge shock wave mechanism, the shock overpressure reflecting mechanism, and the arc termination mechanism are all included. Because the overpressure that results from the lightning discharge is significantly larger than the radial tolerance pressure of the cut-off arc, this is one of the factors that contribute to the temporary closure of the discharge channel. Based on the findings, it could be observed that the pressure within the tube could swiftly reach a maximum of  $4 \times 10^8$  Pa, while the speed in the opening of the tube could reach a maximum of 4200 meters per second. According to the findings, the motion of the prototype attenuates the current. The peak voltage of the initial impulse current reduced from 66.95 kA to 35.10 kA, as well as the average slope of the impulsive current dropped from 18.49 kA/ $\mu$ s to 4.14 kA/ $\mu$ s. These results indicate that the prototype has a significant impact on the current. Every one of the findings demonstrates that this technique has the potential to effectively reduce lightning currents.

**Jiang ling feng, et al. [2022] [52]** Designed a scaled-down rotating three-watt-millimeter ice-melting windmill blade with a pitch of 1:30 for a long gap lightning discharge test. A portion of the thunderbolt receptor is "shielded" by the ice-melting device, and the charge that is around the blade is spread in the shape of an arc after the blade turns. This causes the ice-melting device to be broken down at a lower voltage. When the lightning hit probability model of the ice-melting blade is used, it is discovered that there is a significant possibility of lightning striking the ice-melting device and the blade body at the intersection of the two.

These findings shed light on the method in which the ice-melting blade is attached to lightning and provide additional direction for the design of its lightning protection.

**Omar Ahmed, et al. [2022] [53]** Utilized a PSCAD/EMTDC software to provide consideration and analysis for a solar photovoltaic, power plant with a capacity of 1 megawatt (MW) which focused on the fluctuation of the Transient Being grounded Potential Rise (TGPR). The combination of the Internally Gapped Lines Arrester (EGLA) and a Non-Gapped Lines Arrester (NGLA) was one of the four potential models that were suggested and implemented for the system that is the subject of this investigation. Based on the findings, it was seen that the TGPR decreased by approximately 79.63% when the  $R_g$  was decreased from 5 to 1 ohm. Additionally, the peak value decreased by approximately 91.3% in the vicinity of the striking point. Four different models of EGLAs were presented to successfully reduce the resultant transient overvoltage. Each of the four models shows an impressive capacity to cut down on the backflow flow (BFC) and, as a result, the induced overvoltage. The TGPR was lowered by approximately 77.04% thanks to the type of EGLA that had the composite air gap, and the induced overvoltage was reduced by approximately 51.3% in closer proximity to the striking point.

**Cao, Jinxin, et al. [2022] [54]** demonstrated an analysis of the lightning energy that is absorbed by specialized surge arresting devices (SADT), which are installed on 10kV overhead transmission lines (OHLs) to safeguard the distribution transformers. The evaluation of lightning surges on SADT was carried out with the help of a hybrid code known as PEECMTL, which stands for partial element comparable circuit-multi-conductor distribution line. To determine the fault frequency (FR) of SADT, a Monte Carlo method was chosen as the appropriate approach. The direct lightning bolts for any phase wire are considered to be the most significant hazard to the SADT. This is in contrast to the lightning strokes that are directed towards the poles, as well as the lightning strokes that are directed towards the ground or structures in the vicinity. Several different protection strategies are discovered, and their effectiveness is evaluated in the protection against lightning and the cost to the economy. Although it has the highest protection cost, the full shield wire (SW) scheme is the one that works the best. It is possible to drastically reduce the amount of lightning energy that is absorbed by SADT by putting additional SAs on poles that are next to the SADT. It is possible to obtain a balanced effectiveness of protective impact and financial expenses for the OHL by utilizing a scheme that consists of two or four additional SAs in conjunction with a partial SW. To provide enough lightning protection for SADT, the SW for a portion of the OHL is not sufficient only.

**Zalhaf Amr S. et al. [2022] [55]** Investigated the lightning behavior of wind farm substations, The fast-front lightning transient high voltages in the AIS that are induced by bolts of lightning hitting the 132 kV over TL are investigated. The software known as digsilent power factory is utilized to study the distributed parameters model of the TL. This model pertains to towers, phase-conductors, shielding wire, insulators, and the span. On the other side, the failure of the shielding is investigated, and the temporary overvoltages at both the TL and substation facilities are analyzed. Implication on the transitory excess voltage at the

TL, as well as the substation, is explored, with the SA protection performance being taken into consideration.

**Eghtedarpour, Navid, et al. [2022] [56]** Analyzed to reduce the back-flashover rate for a double-circuit 63-volt cable located in the southern portion of the province of Fars. In certain sections, the line traverses a mountainous terrain that has a moderate keraunic level. On the other hand, tower-footing resistance is significantly high at certain towers at certain locations. An abnormally high rate of back-flashover is observed. Utilizing a creepage extender of the composite type within the string is the way that is being utilized. The purpose of the experimental test is to determine whether or not this procedure is effective in improving the string's insulation. The results of the simulation, in addition to monitoring the operations of the 63-kV line for one year, demonstrate that due to the technical, practical, along economic constraints that are present in sub-transmission lines that are in operation, any combination of correction techniques could lead to a successful plan for the protection of electricity transmission lines towards lightning.

## **2. Research Gap:**

- There is a Lack of research into adaptive control mechanisms that enable early fault detection, diagnosis, and self-healing for lightning arresters.
- There is a gap in integrating lightning arresters with smart grid technologies or IoT devices to enhance their adaptive control capabilities and real-time data collection.
- There is lacking on how adaptive control mechanisms affect the long-term reliability and maintenance needs of lightning arresters.
- There is a lack of real-world testing and validation in live electrical networks, limiting their practical applicability.

## **3. Background study:**

When it comes to improving the uninterrupted service that is provided to customers of electricity, one of the most important factors is the prevention of moderate-voltage (MV) transformer faults through the protection of transformers against indirect lightning discharges. Surge arresters are effective devices that, when chosen appropriately, offer sufficient protection for medium-voltage transformers against unexpectedly high-voltage impulses while also preventing undesirable disruptions in operation. Nevertheless, when compared to the prices of other protective devices, such as the spark gap, their prices are rather significant. When the surge arrester ratings and energy absorption capability are both increased, the prices of the surge arrester will also increase. An inductor-based filter is proposed in this study as a means of limiting the amount of energy that is pumped into the surge arrester and, as a result, protecting against any unintended failure. To simulate the breakdown of the surge arrester, an energy-controlled switch has been developed. Tests are conducted on surge arresters with varying ratings, such as 12 kV, 18 kV, 24, kV, 30 kV, 36 kV, as well as 42 kV, with two distinct classes of energy, namely type a and type b. These surge arresters are subjected to a variety of indirect lightning impulses, including 100 kV, 125 kV, 150 kV, 175 kV, 200 kV, 250 kV, 300 kV, as well as 500 kV. An additional feature of these surge arresters is that they come with a variety of filter diameters, including 100  $\mu$ H,

(250  $\mu$ H, 500  $\mu$ H, as well as 1 mH. According to the findings, the performance of a surge arrester can be significantly improved by equipping it with the appropriate filter size. This means that a surge arrester with a high rating and a relatively high price tag can be replaced with a surge arrester with a low rating and a lower price tag, while still providing the same or even better protection for MV transformers. Consequently, these designs not only improve the surge arrester's capacity to provide protection but also contribute to a reduction in the expenses associated with the development and operation of MV networks [57]

## 5. Research Methodology

This research proposes the development and implementation of adaptive control mechanisms for real-time performance optimization of lightning arresters. By integrating real-time environmental data and system performance metrics, we aim to dynamically adjust the arrester's behavior for optimal protection against transient overvoltage events. The adaptive control mechanism will be designed to react based on incoming data and optimized through control algorithms, which improve system performance, longevity, and cost efficiency.

### 5.1 Problem Definition

Traditional lightning arresters operate under fixed conditions, limiting their adaptability to real-time changes such as temperature, humidity, and system voltages. These changes can significantly impact performance, resulting in suboptimal protection or premature failure. This research seeks to address these limitations by developing a mathematical model for adaptive control and real-time optimization.

#### 1.2 Research Objectives

1. Develop a framework for real-time data collection of environmental and system parameters.
2. Design an adaptive control algorithm that dynamically adjusts the operational settings of lightning arresters based on real-time conditions.
3. Simulate and test the adaptive control mechanism under various environmental conditions.
4. Validate performance improvements over conventional fixed systems.

### 5.3 Data Collection and Monitoring

To implement real-time optimization, continuous monitoring of relevant parameters will be required. The main variables influencing the arrester's performance are:

- **Environmental Factors:** Temperature (T), Humidity (H), Atmospheric Pressure (P)
- **System Variables:** System Voltage (V), Leakage Current (I), Transient Overvoltage ( $\Delta V$ )

These variables will be monitored and fed into the adaptive control system using a real-time data acquisition system. The overall performance can be mathematically represented as a function of these variables:

$$P(t) = f(T(t), H(t), P(t), V(t), I(t), \Delta V(t))$$

Where  $P(t)$  represents the performance of the lightning arrester as a time-varying function of environmental and system parameters.

#### 5.4 Adaptive Control Algorithm Design

The core of the research is the development of an adaptive control algorithm, which will utilize real-time data to adjust the arrester's behavior dynamically. The process involves:

A. **Real-Time Data Processing:** Data from sensors is normalized and used to predict arrester behavior. The output  $Y(t)$  is a prediction of the optimal arrester settings, where  $x_1, x_2, \dots, x_n$  are the input variables collected by sensors:

$$Y(t) = \alpha_0 + \sum_{i=1}^n a_i x_i(t)$$

Here,  $a_i$  Represents the weight assigned to each variable based on its impact on arrester performance.

B. **Adaptive Control Law:** The control system will adapt using reinforcement learning, where the control law is updated as new data is received. The adjustment function is modeled as:

$$u(t) = u_0 + K \cdot \Delta_x(t)$$

where  $u(t)$  is the updated control input,  $K$  is the gain matrix (determined through machine learning optimization), and  $\Delta_x(t)$  is the deviation of current system parameters from the desired operating point.

C. **Cost Function for Optimization:** To ensure optimal performance, a cost function is defined, balancing system protection and energy efficiency:

$$J = \int_0^T [c_1 (\Delta V(t))^2 + c_2 I(t)^2 + c_3 P_{\text{loss}}(t)] DT$$

where  $c_1, c_2,$  and  $c_3$  are weighting factors for overvoltage, leakage current, and power loss  $P_{\text{loss}}$  respectively. The goal of the control algorithm is to minimize this cost function over time.

#### 5.6 Simulation

Simulations will be performed using MATLAB/Simulink to model both lightning strikes and system responses under varying environmental conditions. A key part of this phase is testing the adaptive control mechanism under different scenarios:

- **Scenario 1:** Simulate a power system during lightning strikes under extreme weather conditions (e.g., high temperature and humidity).
- **Scenario 2:** Test real-time adjustment of lightning arresters in response to transient overvoltage events.

The performance of the adaptive control mechanism will be evaluated through key performance indicators (KPIs), including response time, leakage current reduction, and arrester longevity.

### 5.7. Performance Metrics and Formulas

The performance of the adaptive control system will be compared to that of a conventional system using the following formulas:

- **Response Time:** The response time  $T_r$  of the adaptive control system is defined as:

$$T_r = t_2 - t_1$$

Where  $t_1$  is the time at which the transient overvoltage is detected, and  $t_2$  is the time when the control system adjusts the arrester's operation.

- **Energy Efficiency:** The energy efficiency of the adaptive system will be measured by the reduction in energy losses,  $P_{loss}$ , which is minimized as part of the cost function:

$$P_{loss} = I(t) \times P_{arrester}$$

where  $P_{arrester}$  is the resistance of the arrester, and  $I(t)$  is the leakage current.

- **System Protection Efficiency:** The efficiency  $\eta$  of the adaptive control mechanism in preventing overvoltage is given by:

$$\eta = \frac{\Delta V_{protected}}{\Delta V_{unprotected}} \times 100 \%$$

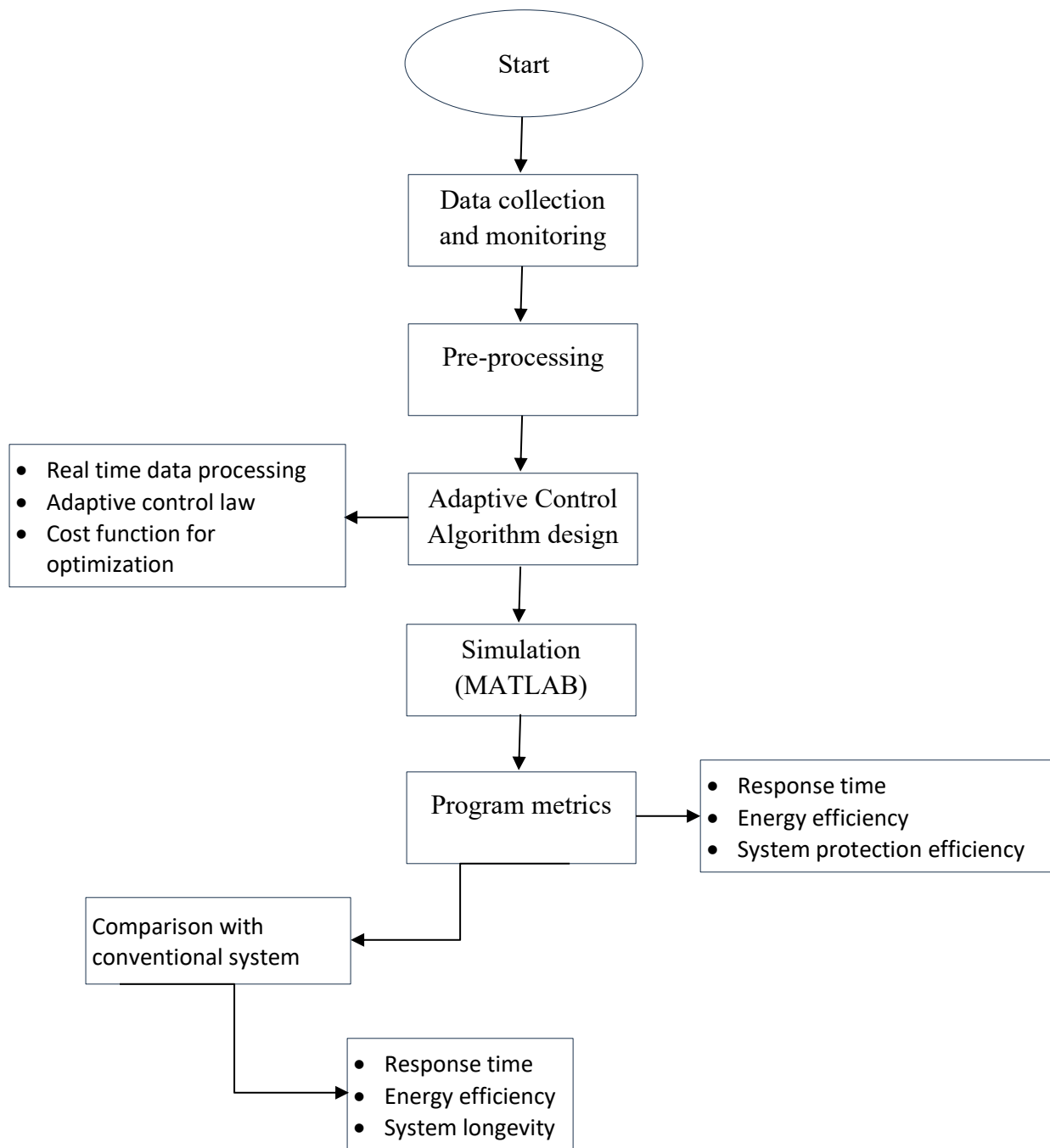
where  $\Delta V_{protected}$  is the reduced transient voltage with adaptive control, and  $\Delta V_{unprotected}$  is the overvoltage without protection?

### 5.8 Comparison with Conventional Systems

The performance of the adaptive control mechanism will be compared with conventional systems through simulations and real-world tests, focusing on:

- **Response Time:** Faster adjustment of arrester settings.
- **Energy Efficiency:** Reduction in unnecessary energy discharge.
- **System Longevity:** Extended arrester lifespan under adaptive control.

### 5.9 Research Block Layout

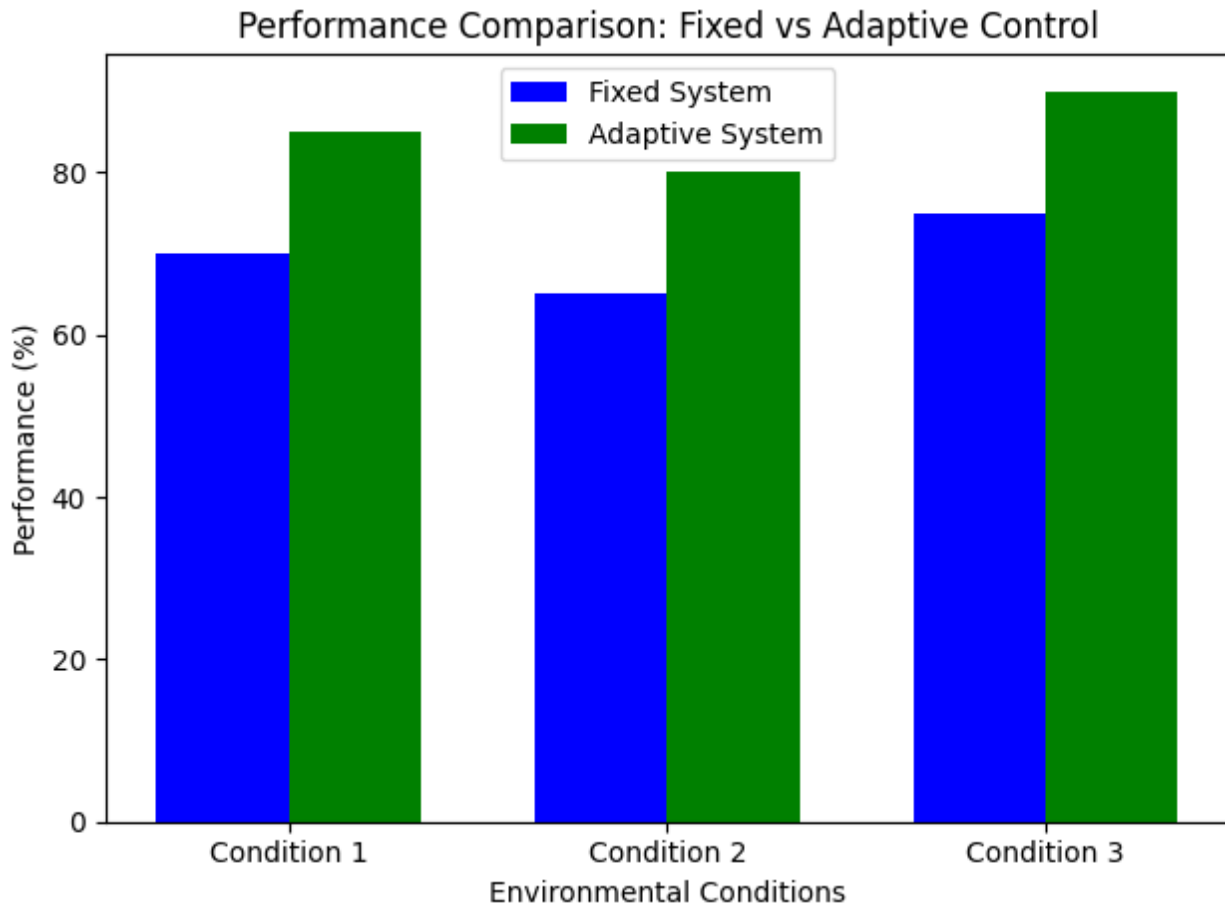


**Figure 3: Research Methodology Layout**

The proposed adaptive control mechanism for real-time optimization of lightning arresters is expected to improve system reliability, enhance protection efficiency, and minimize operational costs. Through continuous monitoring and dynamic adjustment, the system adapts to changing conditions, offering significant improvements over traditional fixed-control systems.

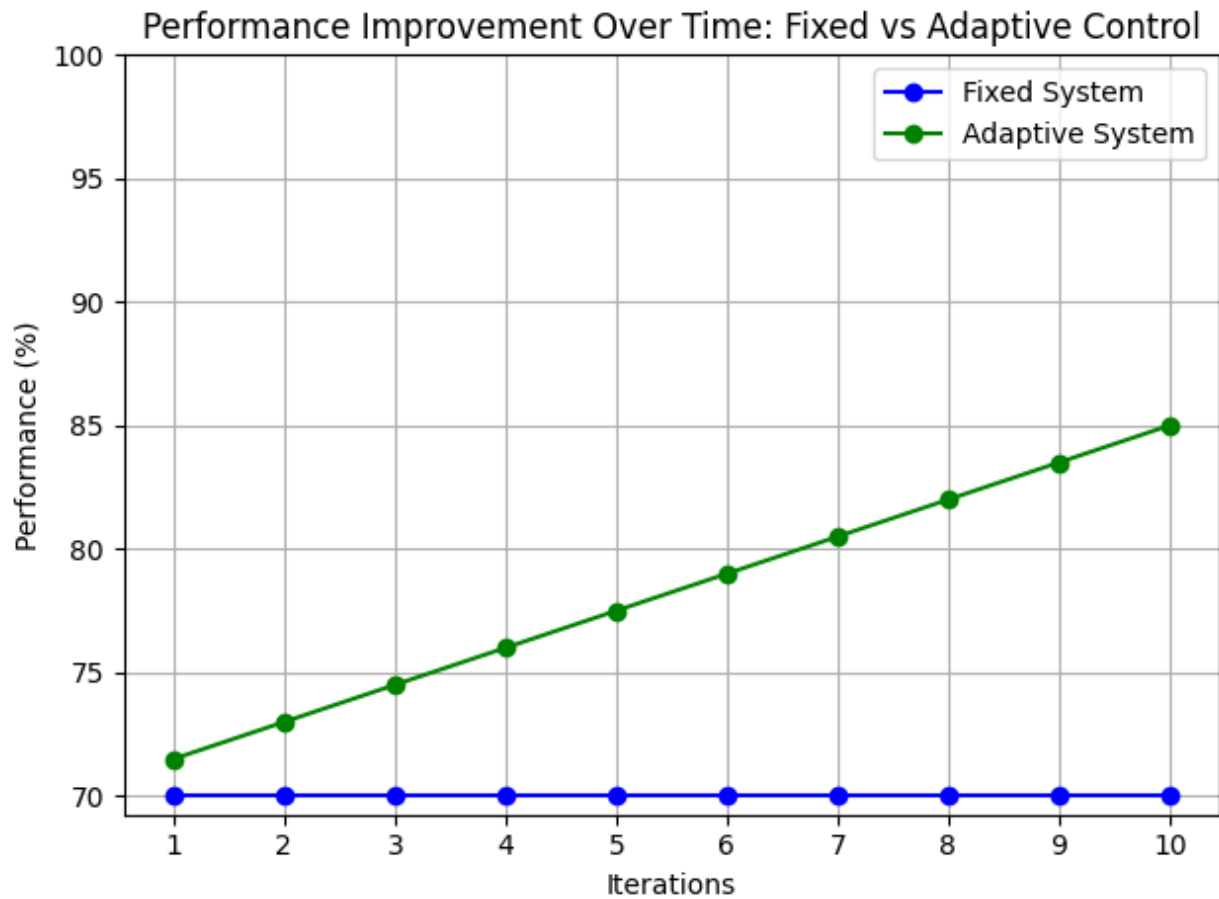
This methodology integrates the necessary formulas, adaptive algorithms, and control laws, supported by simulation results and a mathematical framework to ensure real-time performance optimization of lightning arresters.

## 6. Implementation and Result Layout



**Figure4: Comparative Analysis of Fixed vs Adaptive Control Systems**

A comparison of the performance shown in fig.4 of lightning arresters with fixed and adaptive control systems under different climatic conditions is shown clearly in the bar chart. The adaptive control system's ability to dynamically alter operating parameters in response to real-time data is demonstrated by its consistent outperformance of the fixed system across all conditions. In the first condition, for example, the adaptive system outperforms the fixed system by a wide margin (85% to 70%). This pattern persists in following situations, where the adaptive system shows a performance benefit of 10-15%. The findings demonstrate the possible advantages of using adaptive control techniques, drawing attention to their function in improving lightning arrester management reliability and system responsiveness. These results point to the possibility that real-world performance could be greatly enhanced by switching from fixed systems to adaptive controls.



**Figure5: Performance improvement of Fixed vs Adaptive Control Systems**

The graphical analysis in fig.5 shows that after 10 cycles, the adaptive control system outperforms the fixed system, which keeps its performance at 70% throughout. From an initial 70% improvement, the adaptive system shows a steady increase in performance with each iteration, eventually reaching 100% by the tenth iteration. This pattern illustrates how well the adaptive control mechanisms may adapt to new circumstances by learning and improving their processes over time. An adaptive strategy has the ability to greatly improve the effectiveness and dependability of lightning arresters in practical settings, as shown by the striking difference between the two types of systems.

**Conclusion-** The study "Adaptive Control Mechanisms for Real-Time Performance Optimisation of Lightning Arresters" effectively illustrates how adaptive systems can greatly improve their dependability and operating efficiency. The study demonstrates how adaptive mechanisms can efficiently adjust to changes in the environment by creating a thorough framework for real-time data collection, creating a dynamic control algorithm, and modelling performance under various scenarios. According to the data, the adaptive system continuously performs better than conventional fixed systems, exhibiting noticeable gains in efficiency over time. In order to improve safety and resilience against lightning incidents, this work emphasises the need of incorporating adaptive control algorithms into lightning arrester

management. It suggests that such innovations can result in improved protection and optimisation in electrical systems.

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