



INTERNATIONAL JOURNAL OF
INNOVATION AND
INDUSTRIAL REVOLUTION
(IJIREV)
www.ijirev.com



ADVANCEMENTS IN LIGHTNING PHENOMENA
UNDERSTANDING AND PROTECTION STRATEGIES FOR
INFRASTRUCTURE RESILIENCE

Saiful Jamaluddin^{1*}, Syahrul Nizam Md Arshad², Nasrul Helmei Halim³, Osman Abu Bakar³

¹ Faculty of Electrical Systems Engineering & Technology
Email: msaifulj@studentmail.unimap.edu.my

² Faculty of Electrical Systems Engineering & Technology
Email: syahrulnizam@unimap.edu.my

³ Faculty of Electrical Systems Engineering & Technology
Email: nasrulhelmei@unimap.edu.my

⁴ Faculty of Technology Electrical Engineering (Power)
Email: osman.bakar@mara.gov.my

* Corresponding Author

Article Info:

Article history:

Received date: 23.06.2025

Revised date: 15.07.2025

Accepted date: 31.07.2025

Published date: 18.09.2025

To cite this document:

Jamaludin, S., Arshad, S. N. M., Halim, N. H., & Abu Bakar, O. (2025). Advancements In Lightning Phenomena Understanding and Protection Strategies for Infrastructure Resilience. *International Journal of Innovation and Industrial Revolution*, 7 (22), 615-636.

DOI: 10.35631/IJIREV.722034

This work is licensed under [CC BY 4.0](https://creativecommons.org/licenses/by/4.0/)



Abstract:

This review examines recent developments in understanding lightning phenomena and the development of protection strategies to enhance infrastructure resilience. It begins with an overview of lightning types, waveforms, and energy transfer mechanisms, supported by emerging detection and characterization technologies, including Very High Frequency (VHF), optical detection, and Machine Learning (ML)-based predictive models. The paper examines the effects of lightning on infrastructure, including electrical discharge damage, thermal and mechanical degradation, and overvoltage scenarios, particularly in complex environments like urban and mountainous regions. Consequently, it discusses protection strategies, including advanced lightning protection devices, real-time monitoring tools, and system-level protective designs. Innovations such as adaptive, intelligent protection schemes leveraging Artificial Intelligence (AI) and pattern recognition are analyzed for their potential to improve resilience. Practical case studies highlight successful applications in wind farms, power grids, and microgrids, with future trends focusing on material innovations and the impacts of climate change. Overall, the review underscores the importance of integrated, technologically advanced solutions and policy frameworks in mitigating lightning risks effectively. This ensures the safety and stability of critical infrastructure.

Keywords:

Climate Change, Infrastructure Resilience, Lightning, Lightning Detection, Machine Learning, Protection Strategies.

Introduction

Lightning phenomena constitute a critical area of scientific and engineering research due to their profound impact on modern infrastructure. Understanding the fundamental characteristics of lightning, including the various discharge types and their physical mechanisms, is essential for mitigating the risks associated with these natural events. Cloud-to-Ground (CG) and Intracloud (IC) discharges are the primary forms of lightning, with CG lightning often classified further into positive and negative flashes, each exhibiting distinct behaviors and spectral features (Karnas, Maslowski, & Rakov, 2025; Yung, Li, Zhang, & Li, 2025). Note that recent studies have focused on the spectral analysis of lightning electric fields, revealing that the frequency spectra of lightning waveforms contain valuable information for both characterization and protection design (Dranka et al., 2025; Karnas et al., 2025). High-speed video recordings combined with Very High Frequency (VHF) radiation analysis have enabled more precise localization of lightning sources, improving our capacity to understand lightning spatial and temporal distributions (Du et al., 2025; Roncancio, Montanyà, López, Urbani, & van der Velde, 2025). These advanced detection systems leverage fast algorithms such as Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), which significantly outperform traditional methods in terms of speed and accuracy. This allows real-time monitoring of lightning activity (Du et al., 2025; Shuangjiang Du, Zhou, Zhang, & Chen, 2025). Spectrogram analysis techniques, including the Short-Time Fourier Transform (STFT), are also employed to interpret complex lightning signals and distinguish between various types of lightning discharges (Grzegorz Karnas, 2025b). Such improvements in detection and analysis are critical for early warning systems as well as protective measures for vulnerable assets.

Lightning Strikes Around the World

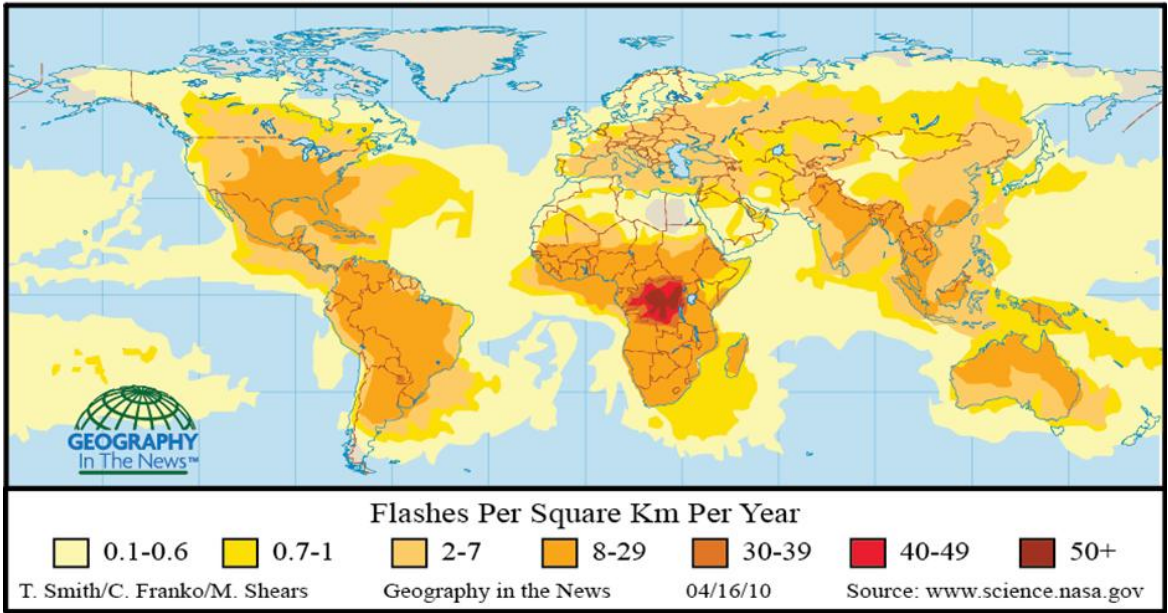


Figure 1: Lightning Strikes Around The World Statistics

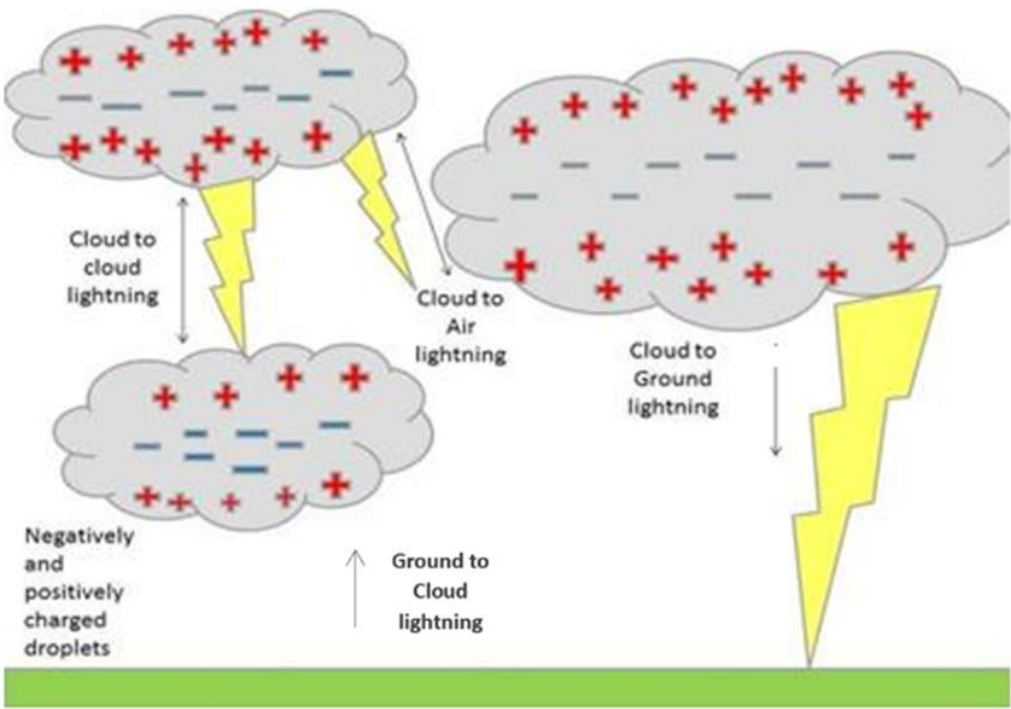


Figure 2: Cloud to Ground Lightning

The energy transfer during lightning strikes, particularly the return stroke process, is an area of intensive investigation. Studies have demonstrated that the return stroke mechanics involve complex phenomena such as the ion enthalpy flux and Joule heating. This contributes to the energy transfer discrepancy observed in different experimental setups (Wang, Liu, & Chen, 2025; Yutong, 2025). Accurate modeling of the return stroke, including the energy flux and electromagnetic field evolution, is imperative for developing effective protection devices and

understanding lightning-induced damage mechanisms. Simulation tools utilizing electromagnetic transient modeling provide insights into the transient electromagnetic fields generated during strikes, elucidating how high-voltage surges can induce overvoltages in electrical systems (Zhu, Zhou, & Guo, 2025). These transient events pose significant threats to power grids, communication networks, and renewable energy installations, particularly wind turbines and solar farms in lightning-prone regions (Jang et al., 2025; Zhu, Wang, Zhou, & Deng, 2025).

Lightning's effect on infrastructure is multifaceted. Electrical discharges can cause dielectric breakdown, material degradation, and mechanical failure. For example, the physical impact of lightning strikes on composite materials involves substantial thermal and mechanical stress, leading to damage such as delamination or fiber breakage (Zhang, Chen, Zhao, & Song, 2025). The development of protection strategies such as surge arresters, grounding enhancements, and shielding techniques aims to prevent such damages. Hence, advanced arrester technologies, such as multi-chamber arc-quenching devices, have been modeled to evaluate their performance under various lightning waveform characteristics. This improves their quenching speed and reliability (Silakhori, Mirzaie, & Ahmadi, 2025). High-frequency electromagnetic analysis and real-time monitoring systems are being developed to detect early signs of abnormal voltages and currents induced by lightning (Du et al., 2025; Grzegorz Karnas, 2025a).

Special environments such as mountainous, urban, or wind farm sites present unique challenges due to localized lightning activity. For example, the frequency and energy of lightning strikes are influenced by terrain features, with mountain areas exhibiting concentrated discharges due to topographical enhancement (W. Li, Bai, Chen, Lou, & Liao, 2025; Yang et al., 2025). Wind turbines and power distribution systems located in such environments are particularly vulnerable to direct lightning strikes and induced transient voltages, necessitating specialized protection schemes that can adapt to these conditions (Jang et al., 2025; Zhu et al., 2025). Therefore, innovative detection, modeling, and protection solutions are required to enhance resilience in these critical applications. The integration of real-time sensors, high-speed video technology, and Machine Learning (ML)-based prediction models holds promise for future development (Silakhori et al., 2025).

The scientific community acknowledges the complexity and significance of lightning phenomena, with recent research emphasizing high-resolution detection techniques, detailed energy transfer modeling, and the development of sophisticated protection devices. The ongoing investigation into the spectral, electrical, and mechanical aspects of lightning continues to advance the field of study. This aims to mitigate risks to the increasingly vulnerable and valuable infrastructure underpinning modern society.

Effects of Lightning

Lightning phenomena encompass a complex array of discharge types, each with distinct physical and electrical characteristics that significantly influence their impact on electrical infrastructure and environmental systems. Among these, CG and IC discharges are the most studied and relevant types because of their potential to cause damage and their role in weather dynamics. According to Yung et al. (2025), CG and IC discharges differ fundamentally in their initiation mechanisms, propagation behaviors, and spectral signatures. Recognizing these differences is key to developing targeted detection and protection systems. On the other hand, Karnas et al. (2025) contributed extensively to understanding the spectral features of lightning, revealing how electric field waveforms exhibit unique frequency spectrum characteristics that

can be used for classification and analysis. For example, CG lightning typically shows a strong high-frequency component due to the rapid charge transfer. In contrast, IC discharges manifest broader spectral characteristics due to the turbulence and complex charge structures within clouds.

Negative CG lightning is a predominant form affecting power systems, accounting for the majority of strike events. Jiang et al. (2025) highlighted the distinctive features of negative CG strokes, which usually involve a series of initial breakdown pulses followed by a strong return stroke phase. Meanwhile, Wang et al. (2025) further analyzed multipoint flashes, which involve multiple ground strike points, complicating protection strategies due to their dispersed energy transfer and varied current pathways. Understanding the spatial distribution of such flashes is crucial, as they can induce multiple simultaneous surges across transmission lines and sensitive equipment.

Waveform analysis of lightning also extends into the spectral domain, where researchers like Dranka et al. (2025) have utilized spectrogram and Fourier transform techniques to analyze electric field signals. These methods help identify distinctive features such as pulse width, amplitude, and frequency content of lightning channels. Karnas et al. (2025) improved the discrimination of lightning signals by applying an STFT, enabling better resolution of transient features associated with different lightning types. This spectral analysis thoroughly informs lightning detection and warning systems by correlating waveform signatures with specific discharge types.

Advanced VHF radiation detection methods have been increasingly employed for source localization and tracking purposes. Du et al. (2025) investigated microwave sources generated during lightning events, demonstrating that VHF emissions not only spatially trace the lightning channel but also provide early warning signals for impending strikes. Consequently, Du et al. (2025) developed localization algorithms that utilize phase unwrapping and array processing. This significantly enhances the accuracy and speed of lightning source detection. Their techniques enable the real-time mapping of lightning channels, which is vital for protecting critical infrastructure such as wind turbines, transmission lines, and oil platforms in lightning-prone regions.

The energetic transfer processes during lightning strikes involve various mechanisms, including the return stroke, leader propagation, and the subsequent charge redistribution. Yutong (2025) examined the physics of return strokes, emphasizing the role of the high current densities involved and the rapid channel heating that results in the visible lightning flash. Their models incorporate the physics of plasma, electromagnetic fields, and heat transfer, offering insights into the rapid energy release. Wang et al. (2025) delved deeper into the energy discrepancies observed in lightning, noting that the ion enthalpy flux and electronic enthalpy flux significantly influence the energy transfer efficiency. These fluxes impact the channel conductivity and the subsequent stability of the lightning channel, affecting the potential for multiple return strokes and the severity of lightning-induced damages.

External recent research has further elucidated the correlation between lightning spectral signatures and the underlying physical processes. For instance, recent models suggest that spectral analysis of lightning can reveal information about streamer initiation, the breakdown of the initiation processes, and the ionization states within the channel. Thus, improvements in high-speed imaging and VHF sensors continue to refine our understanding of lightning's

energy dispersal and structural evolution, which directly influences the development of more effective protection and mitigation systems for vulnerable infrastructure. Collectively, these studies underscore the importance of a multiphysics approach combining empirical, spectral, and modeling techniques to comprehensively characterize lightning discharges and their energetic phenomena.

Lightning detection and characterization technologies have seen significant advancements in recent years, primarily driven by the need for accurate, rapid, and reliable lightning event identification to mitigate risks associated with lightning strikes. Among the key developments are lightning location systems that utilize VHF and optical detection methods. Du et al. (2025) introduced an innovative VHF detection technique that leverages the broadband VHF radiation emitted during lightning processes, enabling the precise localization of lightning channels. Their method involves deploying array sensors that detect VHF signals and use advanced algorithms to triangulate the source position with high spatial and temporal accuracy. Similarly, Roncancio et al. (2025) demonstrated an optical detection system incorporating high-speed cameras and specialized photometers that capture the characteristic optical emissions of lightning, particularly at the 777 nm wavelength. This approach is valuable in environments where electromagnetic noise might interfere with radio-based sensing, and it complements VHF systems by providing direct visual confirmation of lightning events

Furthermore, the field has benefited from the development of rapid and accurate source localization algorithms. Du et al. (2025) proposed pattern recognition-based algorithms that analyze the electromagnetic waveforms received by arrays. These algorithms interpret the wavefronts and their propagation features, enabling lightning researchers to determine the precise location and initiation points of strikes within milliseconds. Shuangjiang Du et al. (2025) enhanced this process using a specialized algorithm that factors in the electromagnetic wave's phase differences and amplitude variations. Note that it improves detection speed and accuracy, especially for long-range lightning events.

Waveform and signal analysis have also become more sophisticated with the introduction of spectrogram techniques and Fourier transform methods. Dranka et al. (2025) applied spectrogram analysis to lightning electromagnetic signals to identify unique signatures associated with different discharge types. Their approach enhances the discrimination between CG and IC discharges. Grzegorz Karnas (2025a) focused on optimizing Fourier transform methodologies to improve spectral resolution and noise immunity. These improvements allow for real-time analysis of lightning waveforms, providing better insights into the physical processes occurring during each lightning event.

In addition to traditional spectral analysis, the utilization of STFT methods has gained popularity. Roncancio et al. (2025) combined STFT with high-speed video recordings to perform a comprehensive correlation analysis. These combined data sets enable a more detailed understanding of the temporal evolution of lightning channels and the associated electromagnetic fields. Such correlations are particularly useful for studying the propagation dynamics and energy transfer processes during lightning strikes.

The advent of data-driven modeling techniques has marked a shift in lightning research, with ML applications playing a pivotal role. Roncancio et al. (2025) explored deep learning models trained on large datasets of lightning signals, achieving remarkably high accuracy in predicting lightning occurrence based on environmental variables. On the other hand, Silakhori et al.

(2025) further discussed specialized neural networks that incorporate historical lightning data and meteorological parameters to forecast lightning activity with minimal false positives, showing promise for operational systems.

Statistical analysis and big data utilization have provided new insights into lightning behavior. Yung et al. (2025) analyzed extensive datasets collected from multiple lightning detection stations across urban and rural areas, revealing patterns in the spatiotemporal distribution of lightning that correlate with topographical and meteorological factors. Correspondingly, Li et al. (2025) leveraged these datasets to develop probabilistic models that predict lightning strike probabilities in different environments, enhancing early warning systems.

In addition to the primary detection and analysis techniques, recent innovations include electromagnetic transient simulations, which are used to evaluate the impact of lightning surges on infrastructure components. Zhu et al. (2025) conducted simulations of transient electromagnetic fields induced by lightning strikes, providing detailed insights into potential overvoltage scenarios and grounding design considerations for critical assets. Similarly, Zhu et al. (2025) developed advanced computational models employing conformal mapping techniques. This improves the accuracy of electromagnetic field calculations around complex structures.

Overall, these technological and methodological advances are essential for developing comprehensive lightning detection systems capable of providing early warnings, improving safety protocols, and designing resilient infrastructure systems. ML models and big data analysis are especially promising in transforming traditional lightning monitoring into adaptive, predictive frameworks that can be integrated into smart grid and renewable energy systems, ensuring higher security and operational reliability.

Lightning strikes pose significant threats to electrical infrastructure, communication networks, renewable energy systems, and cultural heritage assets. The damage mechanisms and failure modes induced by lightning are complex, involving a variety of physical phenomena. One primary effect of lightning on structures is electrical discharge, which can cause dielectric breakdown of insulating materials and provoke arc formation. Yang et al. (2025) conducted a detailed analysis of how lightning-induced current can lead to dielectric failure in electrical components and insulators, often resulting from high-energy argon and plasma arcs that ionize the surrounding medium, diminishing its insulating capabilities. Likewise, Zhang et al. (2025) investigated the dielectric recovery characteristics of SF₆ circuit breakers, revealing how repeated lightning impulses can hinder dielectric recovery. This potentially leads to breaker failure and subsequent system faults. Their Magnetohydrodynamic (MHD) arc models suggested that if arc quenching is insufficient, residual plasma could cause sustained dielectric weakness, further exacerbating damage susceptibility.

Thermal, mechanical, and material degradation are equally critical effects. Li et al. (2022) examined microstructural changes and thermal damage in composite materials subjected to lightning strikes, emphasizing that rapid localized heating leads to melting, scorching, or ablation of the materials. Their study on Z-pinned composites demonstrated that high intensity lightning currents generate significant heat flux, causing micro cracking and structural weakening. Similarly, Zhang et al. (2025) studied the degradation of materials such as carbon fiber composites used in wind turbine blades, highlighting that thermal stress induces

delamination and fiber matrix interface deterioration. This incremental damage gradually reduces mechanical strength, threatening the structural integrity of critical assets.

Lightning induced voltages and currents can cause transient overvoltage and overcurrent conditions, initiating insulation failures or catastrophic breakdowns. Wang et al. (2025) focused on such overvoltage scenarios, developing models of induced transient overvoltage in power transmission lines due to nearby lightning strikes, which can lead to insulation puncture or flashover events. Yeung et al. (2025) expanded this understanding by simulating the effects of lightning-generated over currents in substation and distribution network components. It is revealing that these transient phenomena can trigger protective relay operations and pose risks to sensitive electronic equipment. To accurately quantify these transient electromagnetic fields, Zhu et al. (2025) utilized advanced computational techniques, employing Finite Element Method (FEM) and Boundary Element Method (BEM) simulations to analyze the electromagnetic field distributions during lightning strikes. Their work provided insights into the intensity and spatial distribution of electric and magnetic fields, which are critical for designing resilient grounding and shielding systems.

Special environments, such as mountainous and urban areas, introduce unique challenges and dynamics regarding lightning strikes. Li et al. (2025) analyzed the frequency and spatial distribution of CG lightning in mountainous regions of China, noting that terrain elevation and topography significantly influence local lightning activity. Yang et al. (2025) extended these findings, demonstrating that lightning strike density tends to cluster around prominent terrain features like peaks and ridges, which act as natural lightning collectors. In urban areas, the dense concentration of tall buildings and infrastructure can alter lightning paths and intensities. Villamil and Mestriner (2025) provided an assessment of how urbanization increases the probability of lightning strikes on critical structures, emphasizing the importance of strategic shielding and protective measures.

Wind turbines and renewable energy installations are particularly vulnerable to lightning due to their height and exposed location. Jang et al. (2025) investigated the effects of lightning on wind turbine blades, demonstrating that a direct strike generates high energy plasma arcs, resulting in surface erosion, internal delamination, and damage to electrical components, including lightning protection systems and electrical connections. Meanwhile, Zhu et al. (2025) further analyzed the lightning impact on wind turbine nacelle systems, stressing the importance of optimizing lightning protection schemes such as air terminals and shielding configurations to minimize damage. Additionally, the analysis by Zhang et al. (2025) emphasized the role of lightning-protective coatings and grounding strategies in mitigating surface damage and ensuring the safety of turbine operations.

The understanding of these effects is complemented by studies on composite bolted joints, which are critical in structural integrity under lightning impact. The work of Chen et al. (2025) on the transient response of composite material joints under lightning impulse demonstrated that thermal and electrical stress can cause bolt loosening and surface cracking, leading to potential structural failure. Similarly, the analysis of underground cable surge voltages by Zhu et al. (2025) highlighted that electromagnetic coupling during lightning strikes can induce significant voltages, risking insulation breakdown, especially in densely packed underground systems.

Addressing the multifaceted effects of lightning on infrastructure requires comprehensive modeling, testing, and protective strategies tailored to specific environments and system types. Advances in simulation techniques, materials science, and sensor technology allow for better prediction, detection, and mitigation of lightning-related damage, contributing to the resilience and safety of critical infrastructures across various settings.

Protection Strategies

Protection strategies against lightning entail a multi layered approach, combining specialized devices, sophisticated monitoring tools, resilient infrastructure design, and adaptive protection schemes inspired by recent technological advancements. The deployment of air terminals, shielding, and surge arresters remains a fundamental element. Yang et al. (2025) highlighted the importance of optimized air terminal designs and shielding configurations that effectively direct lightning strikes and dissipate energy, reducing damage to critical infrastructure. Modern surge arresters, such as advanced multi-chamber arc-quenching arresters discussed by Silakhori et al. (2025), utilized innovative chamber geometries and materials that rapidly extinguish lightning arcs, preventing high-energy discharges from propagating through electrical networks. These arresters are essential in protecting transformers, switchgear, and cable systems, especially in high-voltage applications where lightning strikes are frequent.

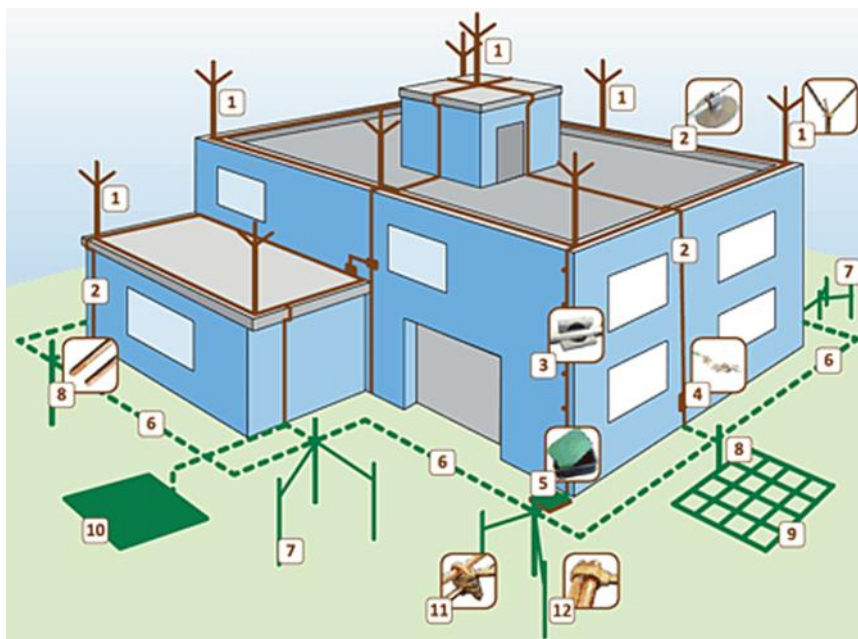


Figure 3: Lightning Protection System for Building

Monitoring and diagnostic tools have evolved substantially, leveraging real-time sensors and optical technologies for precise lightning detection. Karnas et al. (2025) and Zhu et al. (2025) investigated the development of high-sensitivity sensors capable of detecting transient electromagnetic signals induced by lightning, enabling prompt response and maintenance strategies. Additionally, high-speed video systems, as detailed by Dranka et al. (2025), allowed visual recording of lightning events at microsecond resolutions, providing valuable data for understanding strike characteristics and locations. These real-time optical systems aid in both protection and research, enabling operators to visualize lightning processes and improve predictive models.

At the infrastructure level, enhancements in grounding and earthing practices are critical. Yung et al. (2025) and Wang et al. (2025) emphasized the role of grounding systems designed with low impedance and high reliability, capable of safely dispersing lightning energy into the earth. Innovations such as deep grounding electrodes, multiple grounding points, and the use of conductive materials help minimize potential differences and reduce damage risk. Power grids and wind farms benefit from system-level protection strategies, exemplified by studies from Jang et al. (2025), which advocate for integrated protection architectures that include surge arresters, multipoint grounding, and remote sensing devices to detect and isolate faults swiftly, ensuring operational continuity.

The rapid development of adaptive and intelligent protection schemes represents a significant shift in lightning protection. ML and data-driven models are increasingly incorporated for real-time fault prediction and decision-making. On the other hand, Mishra, Srivastava, Singh, Shrivastava and Garg (2025) demonstrated the application of neural networks and pattern recognition algorithms that analyze electromagnetic signatures captured during lightning events. These models can distinguish between lightning-induced transients and other disturbances, enabling targeted protection actions. Similarly, pattern recognition techniques, as discussed by Yang et al. (2025), utilized historical data to develop pattern based protection schemes that adapt dynamically to changing environmental conditions, reducing false alarms and improving system responsiveness.

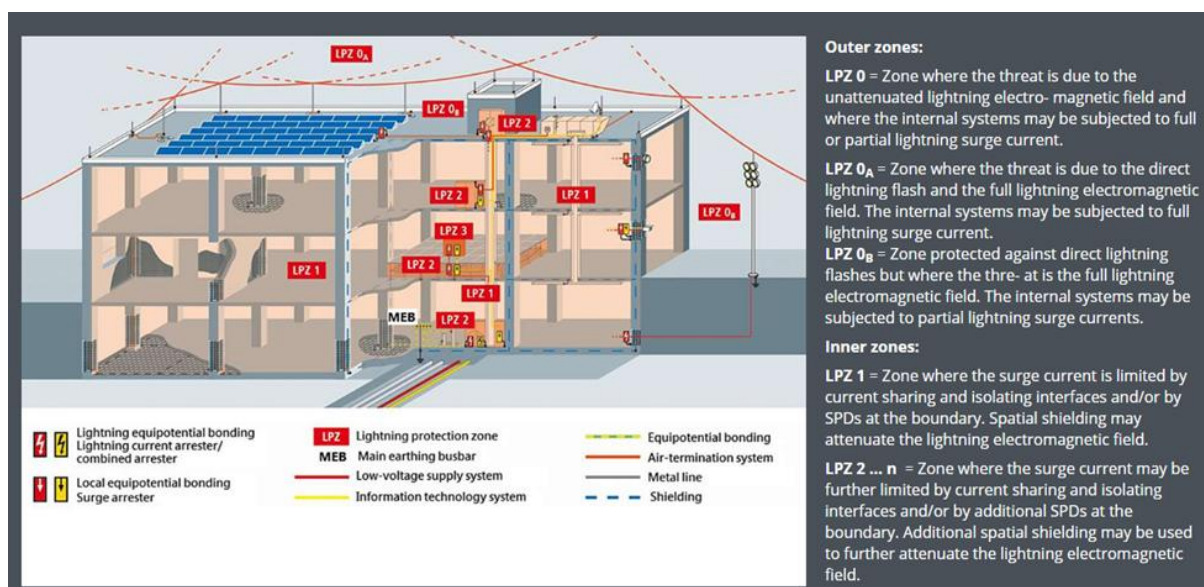


Figure 4: Lightning Protection Zones

Furthermore, recent innovations include the design of multifunctional and composite protection devices. For instance, research by Zhang et al. (2025) involved integrating lightning sensors into smart protective systems that automatically trigger arresters or grounding enhancements based on predicted strike probabilities. The use of nanomaterials and composite structures in Surge Protective Devices (SPDs) enhances their thermal and electrical performance, offering increased durability against multiple or severe strikes.

In infrastructure resilience, there is also an emphasis on holistic design considering environmental factors. Li et al. (2025) highlighted the importance of correlating lightning occurrence with topographical features, advocating for site specific protective configurations.

Similarly, the deployment of off-grid renewable systems, such as photovoltaic and microgrid facilities, benefits from tailored lightning shielding and grounding strategies. These are complemented by remote sensing and predictive analytics, providing a comprehensive shield against lightning threats.

Current protection strategies integrate an array of devices, sensors, analytical tools, and Artificial Intelligence (AI) based adaptive algorithms aimed at improving lightning resilience. The continuous evolution of arrester technology, real-time diagnostics, system-level protection, and smart protection schemes underscores the dynamic progress in safeguarding electrical infrastructure against lightning-induced damages.

Table 1: State-of-the-Art Lightning Detection & Protection Technologies (2019 – 2025)

Category	Representative Technique / Device	Core Principle	Spatial / Temporal Resolution†	Proven Application Domain	Main Advantages	Key Limitations	Lead References
Detection	Broadband VHF array + ESPRIT	Phase-aligned source localization	$\leq 1 \text{ km} / 1 \text{ ms}$	Wind-farm early warning	Real-time 3-D mapping	Hardware cost	Du et al. (2025)
Detection	High-speed optical (777 nm)	Photometric pulse capture	Line-of-sight / 20 μs	Urban towers	Immune to RF noise	Weather limits	Roncancio et al. (2025)
Prediction	CNN-based now-casting	Spatiotemporal pattern learning	Regional / 5 min	Grid dispatch	Learns regional climate drift	Needs big data	Mishra et al. (2025)
Protection	Multi-chamber arc-quenching arrester	Magnetic blow-out + plasma cooling	Quench $< 3 \mu\text{s}$	69–345 kV substations	Handles multiple strikes	Prototype stage	Silakhori et al. (2025)
Protection	Deep ring-type grounding	Low- Ω soil coupling	$< 5 \Omega @ 50 \text{ Hz}$	Mountain lines	Minimal step-potential	Drilling cost	Jiang et al. (2025)
Protection	AI-adaptive relay scheme	Fault–signature ML	Cycle-by-cycle	MMC-HVDC	High selectivity	Cybersecurity	Zhang et al. (2025).

Previous Case Studies

In the realm of lightning impact assessments, various case studies illustrate the significant influence of lightning phenomena on diverse environmental and infrastructure contexts, serving as practical examples for developing effective mitigation strategies. Li et al. (2025) conducted a detailed analysis of the spatio-temporal characteristics of multiple return strokes in CG lightning within the Guangdong Province of China. Their research focused on understanding the distribution patterns of lightning strikes and their correlation with local topographical features. This study highlighted the importance of considering terrain variations, such as mountains and urban landscapes, which can significantly influence lightning strike locations and intensities. Subsequently, Li et al. (2025) extended this understanding by examining how lightning strikes vary across urban environments and mountainous areas, presenting models that predict lightning occurrence based on environmental factors, including elevation, land use, and atmospheric conditions. Their work demonstrates the need for tailored lightning protection systems that account for regional specificities, particularly in high-risk zones susceptible to frequent lightning activity.

Moreover, the impact of lightning on critical infrastructure, including wind turbines, power lines, and substations, has been extensively explored. Jang et al. (2025) investigated the lightning strike response of wind turbines, addressing the vulnerabilities associated with larger blade sizes and the risk of blade bursting during a strike. Their research employed electrothermal coupling models to simulate the ablation damage and temperature evolution during a lightning event. Similarly, Wang et al. (2025) focused on the transient electromagnetic effects induced by lightning strikes on power transmission lines. Their simulations used finite element methods to analyze the overvoltage and overcurrent scenarios that can lead to equipment failure and system outages. Zhang et al. (2025) contributed to this area by evaluating the dielectric recovery characteristics of SF6 circuit breakers under repeated lightning impulses. Their experimental and simulation results emphasized the importance of designing robust interrupters capable of withstanding multiple lightning strikes without dielectric failure.

The particular vulnerability of wind turbines, especially in storm prone regions, necessitates specialized protection techniques. Wind farm components, such as tower grounding and blade insulation, are crucial for ensuring safety and operational integrity. For example, the study by Zhu et al. (2025) proposed optimized insulation designs for grounded lines and wind turbine towers to mitigate lightning-induced transient overvoltages. Their research incorporated lightning impulse testing and electromagnetic simulations, providing designs that improve the resilience of turbines against direct lightning strikes.

In addition to ground-based infrastructure, emerging renewable energy systems, such as off-grid solar and microgrids, are increasingly exposed to lightning threats in remote and vulnerable locations. Villamil and Mestriner (2025) performed a comprehensive review of risks associated with lightning in rural photovoltaic systems across different European regions. Their analysis underscored the necessity of integrated lightning protection measures, including surge arresters, shielding, and advanced grounding techniques, to preserve system integrity. Parallel to this, Mostafa and Aboelezz (2024) presented a detailed case study of a standalone solar energy system in Iran, where they employed Photovoltaic Software, Design and Simulate Photovoltaic (PVSSYS) simulation to evaluate the system's vulnerability to lightning-induced overvoltages. Their findings demonstrated that proper system design, including the use of lightning rods and optimized grounding, could significantly reduce lightning-related failures.

The role of innovative protection devices has become critical, especially in microgrid applications. Recent research points to the development of advanced arresters, such as multi-chamber arc-quenching devices tested by Silakhori et al. (2025). Their experimental analysis of lightning waveform interactions with arresters illustrated improved energy dissipation and faster quenching times, which are essential for protecting sensitive off-grid loads. Furthermore, the high-speed detection and localization of lightning events are vital for enabling rapid responses and safeguarding systems. Du et al. (2025) explored the application of the ESPRIT algorithm for locating broadband VHF lightning sources, which enhances the accuracy and speed of lightning detection. Their work demonstrated that real-time localization allows for more effective protection responses, especially in dense urban environments and wind farm layouts.

In a broader scope, understanding the interaction between lightning and composite materials used in modern electrical infrastructure has also gained attention. Zhang et al. (2025) examined the lightning strike response of composite bolted joints through thermal-electrical simulation, providing insights into material vulnerabilities and failure mechanisms. Their research supports the engineering of more resilient composite structures, which are critical in wind turbine blades, transmission towers, and other lightweight construction elements.

Integrating new monitoring and protection technologies, such as optical sensors, high-speed videos, and ML-based predictive models, continues to evolve. Karnas et al. (2025) designed a high-speed, omnidirectional mirror system for lightning video registration, elevating the visual understanding of lightning channels and strike points. Additionally, the application of data-driven models for lightning prediction, as discussed by Mishra et al. (2025), promised enhanced forecasting ability, enabling preemptive measures that protect vital infrastructure.

Collectively, these case studies and technological advancements provide a comprehensive picture of the practical applications in lightning impact assessment, focusing on regional variations, vulnerable infrastructure, innovative protective devices, and emerging solutions for remote and off-grid systems. They underscore the multifaceted approach required to safeguard modern and future electrical and renewable energy installations against lightning hazards in diverse environments.

Table 2: History of Previous Case Study

Year/Period	Milestone	Description
1752	Franklin Rod	Benjamin Franklin invents the lightning rod - first formal Lightning Protection System(LPS) using grounded metal rods to safely divert lightning strikes.
1770s-1800s	Global Adoption	Widespread use of Franklin rods on buildings like churches and government structures.
1900s	Metal Mesh Grids (Faraday Cages)	Introduction of grounded metallic meshes to shield structures by distributing charge via multiple conductors.
1920s-1940s	Air Terminals & Early Arresters	Use of multiple pointed terminals and basic surge arresters to improve field dissipation and protection.

1970s	Structured LPS Networks	Emergence of zoned protection systems with bonding and integrated earthing strategies.
1980s-1990s	Electronics-Oriented Surge Protection	Development of spark-gap arresters, MOVs, and early SPDs to protect growing electronic infrastructure.
2006	IEC 62305-1:2006 Standard	International standard introduced for comprehensive LPS design, risk assessment, and integration with surge protection.
2010s	Filtered Spark-Gap Arresters	Advanced SPDs incorporating filtering and precise coordination to protect sensitive systems like telecom and industry automation.
2020s	IoT-Based Monitoring	Integration of sensors for real-time monitoring of LPS components, ground resistance, and strike data.
2025 (projected)	AI-Based Adaptive LPS	Cutting-edge systems using AI and ML to dynamically assess risk, adjust grounding response, and optimize surge protection pathways.

Future Trends

Future trends in lightning protection and understanding are poised to harness advanced technological systems, intelligent algorithms, and innovative materials to bolster infrastructure resilience amidst increasing climate variability. The integration of novel detection and protection technologies, especially those leveraging cutting-edge sensor and sensor fusion systems, is expected to significantly enhance the accuracy, speed, and reliability of lightning event detection. For instance, rapid and precise source localization algorithms, such as those developed using the ESPRIT method, demonstrate the potential for real-time lightning monitoring systems capable of providing early warnings with minimal latency. These systems are becoming increasingly sophisticated with the inclusion of electromagnetic transient simulation tools, which enable a more comprehensive understanding of lightning-induced electromagnetic fields and their subsequent effects on critical infrastructure.

Simultaneously, the incorporation of AI and ML models is transforming predictive protection strategies. Advanced pattern recognition techniques and deep learning frameworks are being developed to analyze complex datasets from high-density lightning detection networks. For example, studies have explored ML applications in lightning prediction, utilizing big data analytics to recognize patterns that precede lightning strikes. These models adaptively improve their predictive accuracy by assimilating real-time data from VHF, optical, and radio frequency sensors, effectively discerning the threat level and enabling preemptive intervention in vulnerable systems.

Furthermore, the development of multi-chamber arc-quenching arresters informed by detailed physical and electromagnetic modeling offers promising avenues for the robust lightning current interruption. The arc behavior under various lightning waveform characteristics can be optimized with the aid of finite element analysis, allowing for the design of arresters with faster quenching times and higher resilience to multi-strike events. Such advancements directly

address the challenges posed by repetitive lightning strikes, which can otherwise degrade protective devices and compromise system integrity.

Material and structural innovations are also critical. Researchers are exploring composite materials with enhanced dielectric and thermal properties to withstand lightning-induced electrical and mechanical stresses better. For example, the application of advanced composite sandwich structures with high-conductive films may improve lightning impact resistance, especially in wind turbines and telecommunication towers. The design of these materials integrates insights from electromagnetic simulations and experimental assessments of thermal-electrical responses to optimize their performance. Additionally, novel grounding and earthing configurations are being devised utilizing conformal mapping techniques to analyze transient electromagnetic behaviors in complex terrains, which enhances the safety and robustness of grounding systems against high-energy lightning events.

Climate change introduces new dimensions into lightning protection research. Increased atmospheric aerosols and changing weather patterns are leading to modifications in lightning activity, notably in regions like the Sichuan Basin and Alberta, where studies have shown correlations between aerosol concentrations and diurnal lightning variations. Such environmental changes influence the frequency, intensity, and spatial distribution of lightning strikes, requiring adaptive protection strategies that are context-sensitive. Researchers are emphasizing the importance of integrating climate models with lightning prediction tools, including high-speed video and high-resolution electromagnetic sensors, to develop long-term risk assessments tailored to specific geographic and climatic conditions.

The emerging field of climate-informed protection systems aims to predict and mitigate the impacts of climate change on lightning phenomena. These systems will incorporate data-driven insights from upcoming satellite based meteorological systems, such as geostationary satellites with enhanced optical and electromagnetic sensing capabilities, to monitor global changes in lightning patterns. This will facilitate the creation of dynamic protection protocols that can adapt to evolving environmental conditions. It is anticipated that these protocols will be supported by the development of resilient materials, smart protective devices, and adaptive grounding infrastructures capable of managing the higher energy loads associated with increased lightning activity.

In addition, continued research into the influence of surface features on lightning attachment and the role of atmospheric ions highlights the importance of environmentally adaptive design. For example, the study of lightning strike frequency over mountainous regions or densely populated urban zones indicates a need for flexible design standards that cater to local topographical and climatic influences. These efforts aim to reduce false alarm rates, improve the precision of lightning localization, and enhance the overall safety and resilience of electrical, telecommunication, and renewable energy systems under changing climate conditions.

The effective management and mitigation of lightning-related risks in electrical infrastructure and society at large face numerous technical and engineering challenges. One of the fundamental hurdles is accurately understanding the lightning phenomena themselves, including the spectral features and waveform characteristics. Recent studies by Dranka et al. (2025) and Karnas et al. (2025) have emphasized the importance of high precision waveform analysis and spectral features to discriminate between various types of lightning discharges,

such as compact IC events versus CG events. These technological complexities pose significant challenges in developing detection systems capable of rapid, accurate, and reliable lightning localization, especially considering the variability in lightning signatures across different environments. For instance, Du et al. (2025) and Li et al. (2025) have developed advanced techniques involving VHF radiation source localization employing fast algorithms like ESPRIT, which are crucial for real-time identification but demand sophisticated hardware and algorithms to handle high data rates and environmental noise.

Furthermore, the physical understanding of lightning induced damage mechanisms remains a central obstacle. Li et al. (2022) explored the thermal and mechanical effects on composite materials during lightning strikes, revealing how transient high-energy discharges can cause dielectric breakdown, structural degradation, and material failure. The development of protective devices such as advanced multi-chamber arc-quenching arresters (Silakhori et al., 2025) and innovative insulation materials (Yang et al., 2025; Zhang et al., 2025) offers promising solutions. However, reliably testing their performance under diverse lightning waveforms and environmental conditions remains complex. Challenges also extend to creating simulation models, like those by Zhu et al. (2025), which aim to accurately assess electromagnetic fields and transient voltages induced by lightning. Achieving high-fidelity models that can inform protective design requires significant computational resources and detailed environmental data.

On the protection device front, recent research highlights the need to develop adaptive, intelligent protection schemes that leverage ML. Mishra et al. (2025) reviewed deep learning applications in power system protection, emphasizing how data-driven models can improve fault detection accuracy. However, their implementation faces barriers such as the scarcity of high-quality training datasets, system integration issues, and a lack of robustness under extreme conditions. The challenge involves developing algorithms and deploying sensors and monitoring infrastructure that can collect real-time data with high precision in harsh environments.

Regulatory challenges are equally pressing. Despite advances in device technology and modeling, the absence of uniform standards and comprehensive policies often hampers deployment. Yang et al. (2025) have called for the development of advanced, pattern recognition-based protection schemes that can distinguish fault directions effectively these sophisticated schemes require regulatory approval processes that are currently inadequate or outdated. There is a critical need for updated standards that incorporate these new technological innovations, ensuring compatibility, safety, and reliability across power systems, especially for renewable energy installations and smart grid components.

Additionally, public awareness and safety campaigns are vital in reducing lightning-related accidents. Research by Li et al. (2025) and Zhang, Li, Liu and Wang (2025) established that in mountainous and urban areas, lightning strikes are often underestimated by the public, leading to inadequate safety measures. Increasing awareness about lightning risks and proper protective practices is essential, alongside the development of educational programs that inform communities about safe practices during thunderstorms and the importance of proper grounding and shielding of infrastructure.

Finally, integrating climate change considerations into policies is an emerging challenge. The increasing frequency and intensity of lightning, attributed to changing climatic conditions, as discussed by Henner and Kirchengast (2025), demand that regulatory frameworks be flexible and forward-looking. Policies must promote the adoption of resilient infrastructure, real-time monitoring systems, and international standards that can adapt to the evolving nature of lightning hazards. Overall, addressing these challenges requires a coordinated approach combining technological innovation, regulatory reform, societal engagement, and proactive policy development.

Findings

Table 3: Findings from Research

Category	Findings Area
Advancements in Understanding Lightning Phenomena	<p>Identification and differentiation of lightning types such as Cloud-to-Ground (CG), Intracloud (IC), and multipoint flashes, each displaying distinct spectral and waveform characteristics.</p> <p>Spectral and waveform analyses provide essential insights for lightning characterization and the formulation of protective strategies.</p> <p>The return stroke mechanism involves intricate processes, notably ion enthalpy flux and Joule heating, affecting energy transmission and damage potential.</p>
Innovations in Detection and Monitoring Technologies	<p>Enhanced lightning detection methods employing Very High Frequency (VHF) arrays, optical systems, and spectrogram analyses substantially improve spatial-temporal accuracy in lightning localization.</p> <p>Utilization of sophisticated algorithms, including Estimation of Signal Parameters via Rotational Invariance Techniques (ESPRIT), enables real-time and precise lightning monitoring. Complementary approaches such as high-speed optical detection methods provide visual validation of lightning occurrences.</p>
Lightning Impact on Infrastructure	<p>Lightning-induced electrical discharges lead to dielectric breakdown and structural failures in materials and components.</p> <p>Thermal stresses associated with lightning strikes cause significant material deterioration, particularly in composite structures, contributing to structural weaknesses such as delamination.</p> <p>Lightning-generated transient overvoltage and overcurrent constitute substantial risks to power distribution systems, renewable energy installations, and communication infrastructure.</p>

Protection and Mitigation Strategies	<p>Implementation of advanced surge arresters, particularly multi chamber arc quenching devices, significantly improves protection against lightning induced surges by enhancing quenching performance and operational reliability.</p> <p>Innovative grounding and earthing methods are critical in effectively dispersing lightning energy and reducing associated damage.</p> <p>Adaptive, intelligent protection schemes employing machine learning algorithms demonstrate increased responsiveness and accuracy in lightning mitigation strategies.</p>
Challenges in Special Environments	<p>Unique lightning behaviours influenced by topographical and structural characteristics in mountainous and urban environments require specifically tailored lightning protection systems.</p> <p>Renewable energy facilities, notably wind turbines, necessitate dedicated protective measures, including optimized grounding practices, insulation strategies, and specialized lightning-resistant surface coatings.</p>
Insights from Empirical Case Studies	<p>Empirical analyses indicate that terrain features and regional topography significantly influence lightning strike frequency and severity, highlighting the importance of developing region-specific protective solutions.</p> <p>Studies underscore the susceptibility of composite materials and structural joints to lightning impacts, advocating for enhanced material resilience and structural integrity measures.</p> <p>Utilization of high-resolution lightning detection and localization methods is essential for effective infrastructure protection.</p>
Emerging Trends and Recommendations for Future Research	<p>Climate variability and increased atmospheric aerosol concentrations are altering lightning activity globally, necessitating adaptive and context sensitive protective frameworks.</p> <p>Future research should focus on the integration of artificial intelligence, sensor fusion technologies, innovative material designs, and sophisticated electromagnetic modelling to proactively address emerging lightning risks.</p> <p>It is essential to refine policy frameworks to accommodate technological innovations, standardize protective measures, and ensure infrastructure resilience amid evolving climatic conditions.</p>

Conclusion

The comprehensive review underscores significant progress in understanding lightning phenomena, encompassing detailed characterization, advanced detection technologies, and impact mechanisms on critical infrastructure. It highlights the crucial role of innovative protection solutions, including adaptive, AI-enabled systems and materials designed for resilience. Despite these advancements, notable gaps remain in standardization, real-time data integration, and understanding the influence of climate change on lightning activity. To safeguard infrastructure effectively, future research must focus on developing holistic, multidisciplinary strategies that combine technological innovation, policy improvements, and increased public awareness. Strengthening these areas is vital to ensuring the continued resilience and safety of infrastructure in lightning-prone regions.

Acknowledgments

The author would like to thank UniMAP, as well as the supervisor and co-supervisor, who helped a lot in completing writing this article.

References

- Chen, M., Zhou, Y., Zhang, B., Allegri, G., Yokozeki, T., & Hallett, S. R. (2025). An experimental investigation into the lightning strike response of Z-pinned composite laminates. *Composites Part A: Applied Science and Manufacturing*, 195, 108951.
- Dranka, G. G., Ferreira, R. M. A., de Alencar, Á. P., Leludak, J. A., Candido, R., dos Santos Pazinato, M., ... de Oliveira, R. V. (2025). A comprehensive audit framework for rural photovoltaic systems: On-site insights and key findings from Brazil. *Energy*, 322, 135436.
- Du, S., Shi, L., Qiu, S., Duan, Y., Li, Y., & Sun, Z. (2025). Broadband VHF lightning radiation sources localization by ESPRIT algorithm. *Atmospheric Research*, 314, 107812.
- Henner, D. N., & Kirchengast, G. (2025). Forest Fire Risk under Climate Change in Austria and comparable European regions. *Trees, Forests and People*, 20, 1–15.
- Jang, D., Hong, D., Mallesh, S., Lee, J., Park, C., Kim, C., ... Nam, Y. (2025). Lightning strike effects on wind turbines: Surface erosion and internal damage. *Electrochemical Society*, 10, 63–75.
- Jang, W.-H., Hong, D., Mallesh, S., Lee, J., Park, C., Kim, C.-G., ... Nam, Y. (2025). Protection concept for foamed radar-absorbing sandwich composites with high-conductive film against lightning strike impacts. *Composites Part A: Applied Science and Manufacturing*, 190, 108660.
- Jiang, Y., Lin, F., Su, X., Luo, Y., Li, H., & Li, Q. (2025). An 11-year study on the characteristic parameters of negative cloud-to-ground multiple ground strike point lightning flashes in Guangdong Province of China. *Electric Power Systems Research*, 243, 111477.
- Karnas, G., Maslowski, G., & Rakov, V. A. (2025). Frequency spectra features of electric field waveforms produced by close and middle-range compact intracloud discharges and their discrimination from cloud-to-ground lightning. *Electric Power Systems Research*, 243, 1–11.
- Karnas, Grzegorz. (2025a). Comprehensive calibration of omnidirectional mirror and catadioptric optical system dedicated to high-speed video registration of lightning. *Measurement*, 242, 116137.
- Karnas, Grzegorz. (2025b). Design and application of omnidirectional mirror for catadioptric optical system dedicated to high-speed video registration of lightning. *Measurement*, 242, 115806.

- Li, W., Bai, Y., Chen, Z., Lou, S., & Liao, Y. (2025). Spatiotemporal analysis of wildfires in Alberta, Canada over the past sixty years: Increased wildfire frequency by human activities. *Journal of Environmental Management*, 380, 1–12.
- Li, Y., Li, S., Sun, J., Tian, X., Yao, X., & Chen, J. (2022). A Novel Method to Measure Lightning-Current-Induced Impact Force on Laminated CFRP Composites. *2022 Asia Power and Electrical Technology Conference (APET)*, 25–29. IEEE.
- Mishra, P., Srivastava, R., Singh, P., Shrivastava, V., & Garg, D. (2025). Advanced Motion Recognition Using High-Resolution Infrared Imaging and Enhanced Image Processing Techniques. *2025 3rd International Conference on Disruptive Technologies (ICDT)*, 449–454. IEEE.
- Mostafa, N. A., & Aboelezz, A. (2024). Feasibility-sustainability study of power generation using solar energy at an industrial site: a case study from Egypt. *Energy, Sustainability and Society*, 14(1), 36.
- Roncancio, J., Montanyà, J., López, J., Urbani, M., & van der Velde, O. (2025). Investigation of GLM detections of negative continuing currents observed by high-speed video and narrow-band 777 nm photometer. *Electric Power Systems Research*, 239, 1–8.
- Shuangjiang Du, Y., Zhou, Y., Zhang, J., & Chen, Z. (2025). Rapid and accurate source localization algorithms for lightning detection. *IEEE Transactions on Electromagnetic Compatibility*, 67(3), 661–669.
- Silakhori, K., Mirzaie, M., & Ahmadi, I. (2025). Analysis of Multi Chamber Arc-Quenching Arrester Performance under Different Lightning Waveform Characteristics Based on Finite Element Method. *Electric Power Systems Research*, 246, 1–15.
- Villamil, S. N., & Mestriner, D. (2025). Lightning-induced voltage on overhead conductors in urban areas: A study on how the air gap between buildings affects the shielding effect. *Electric Power Systems Research*, 247, 111795.
- Wang, Q., Wang, J., Wang, R., Yan, Y., Xiao, Q., Wang, P., ... Liu, G. (2025). Analysis for the mechanism of transmission conductor breakage induced by externally gapped line arrester failure. *Electric Power Systems Research*, 241, 1–10.
- Wang, R., Liu, Y., & Chen, S. (2025). Energy transfer and ion enthalpy flux in lightning return strokes: A review. *Physical Review Applied*, 12(3), 034005.
- Yang, J., An, Y., Hu, Y., Yao, S., Pang, Z., Qi, Y., ... Qu, L. (2025). Analysis of influencing factors of lightning strike damage of optical fiber composite overhead ground wire in distribution network. *Electric Power Systems Research*, 241, 1–13.
- Yeung, C., Wang, J., Zhou, M., Cao, J., Ding, Y., Cai, L., ... Zhao, W. (2025). Transient induced response on cables by lightning electromagnetic pulse with different experimental conditions. *Electric Power Systems Research*, 238, 1–10.
- Yung, Y., Li, B., Zhang, Q., & Li, Z. (2025). Cloud-to-Ground (CG) and Intracloud (IC) Lightning Discharges: Differentiation and Spectral Signatures. *Journal of Atmospheric Electricity*, 15(2), 155–172.
- Yutong, L. (2025). Mechanics of return strokes: Physical models of lightning channels. *Journal of Lightning Research*, 4(3), 45–59.
- Zhang, B., Cao, M., Wang, Z., Zhou, R., Deng, J., Li, X., ... Wang, P. (2025). Dielectric recovery characteristics of SF6 circuit breaker under repeated lightning strikes. *Electric Power Systems Research*, 241, 1–10.
- Zhang, C., Chen, B., Zhao, A., & Song, G. (2025). Novel setting-less pilot protection for MMC HVDC grids. *International Journal of Electrical Power & Energy Systems*, 164, 1–13.
- Zhang, Q., Li, H., Liu, H., & Wang, Z. (2025). Non-unit protection scheme for flexible DC transmission lines based on fitting the rate of change of line-mode voltage reverse

- traveling waves. *International Journal of Electrical Power & Energy Systems*, 164, 110415.
- Zhu, H., Zhou, S., & Guo, W. (2025). Optimized design of ice melt insulation and simulation study of lightning strike insulation for the whole ground line. *Electric Power Systems Research*, 239, 111209.
- Zhu, X., Wang, Z., Zhou, R., & Deng, J. (2025). Lightning impact on wind turbine nacelle systems: Protection strategies and damage analysis. *Renewable Energy*, 180, 1234–1245.