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FELINES

Forecast of the Effects of Lightning IN Electrical Systems

Deliverable II: **Effects of Lighting**

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Executive Summary

This document shortly lists the most frequently reported adverse effects of direct and indirect lightnings on sensible equipment. It represents the second deliverable of the research project FELINES (Forecast of the Effects of Lightning IN Electrical Systems), financed by the Italian Ministry of Research under the PRIN 2022 call.

FELINES aims at designing a protection system capable of sensing electromagnetic fields that are preliminary to a lightning event, and consequently disconnect part (or all) of the electric infrastructure under its protection. These fields are generated by the so-called *Preliminary Breakdown Pulses* (PBP), localized events taking place during the first phases of the lightning inception.

For the sake of exposition, Lightning Adverse Effect(s) (LAEs) have been categorized in this report according to the equipment type, limiting to the most relevant cases:

a) LAE on power distribution lines;
b) LAE on photovoltaic plants;
c) LAE on wind farms;
d) LAE on buildings and other equipment.

All of them includes both direct and indirect lightnings. While for direct hits several possible countermeasures are available, for the indirect lighting events the protection of the sensible equipment is much more difficult. The indirect lightning is more likely to happen in open field installations, and in this report both cases are considered. The source of data is a survey of the most recent publications about these topics, starting from 2014.

Contents

1. Introduction

In this introduction we report a description of the main lines of the *FELINES* project, supported by relevant elements from the bibliography used during the preparation of research project (reported here for the sake of readability).

Lightning is a large-scale natural spark discharge that occurs within the atmosphere or between the atmosphere and the earth's surface. In an initial phase, within the atmosphere, positive and negative electric charges form due to processes like ionization of air molecules by some high-energy phenomenon (e.g. cosmic rays). In a thundercloud, water droplets (hydrometeors) and ice crystals move rapidly upward and downward, separating and concentrating these charges. Negative charges accumulate at the cloud's base, while positive charges gather toward the top. This phase is generally associated with electromagnetic waves generating signals called Preliminary Breakdown Pulses (PBP). The process than evolves, occasionally generating electric fields large enough to overcome the (wet) air electric rigidity and generating a discharge.

The phenomena associated with such Lightning Events (LE) represent a critical issue for the electrical infrastructures. Among them, LE mostly impact the electric power transmission and distribution systems, but also renewable energy sources – mostly PhotoVoltaic (PV) plants and Wind Farms (WF) - and electronic devices, either outdoor or within civil buildings, are sensible to such damages.

When dealing with damages due to LE, it is possible to distinguish between two categories: *direct strikes* and *indirect strikes* (the lightning hits the ground nearby the EI).

Electronic devices can suffer significant damage due to direct strikes. A few examples are:

- *Electrical Overloads:* A direct lightning strike can introduce an enormous surge of electrical current into the device or the system (e.g. from the power lines). This surge can overwhelm electronic devices, causing electrical overload. Components like circuit boards, transformers, and power supplies may fail due to excessive current.
- *Component Destruction:* High-voltage surges can fry delicate components within devices. Integrated circuits, capacitors, and resistors may be irreparably damaged.
- *Fire Hazard:* Intense heat from a lightning strike can ignite flammable materials. Damaged wiring, insulation, or electronic components can lead to electrical fires.
- *Communication Disruptions:* Lightning-induced surges can affect communication lines (telephone, internet, etc.). Modems, routers, and network switches may fail or experience connectivity issues.
- *Antenna Damage:* Lightning often strikes antennas, satellite dishes, or communication towers. Devices connected to these structures (TVs, radios, etc.) can suffer damage.

While direct hits are much more dangerous, indirect ones have a higher occurrence probability, which leads to a greater number of faults. A few examples are:

- *Effects of induced currents*: The ElectroMagnetic Pulse (EMP) generated by a nearby lightning strike can induce unwanted currents into nearby electrical wiring and devices. These induced currents can disrupt the normal operation of electronic equipment, causing malfunctions, data loss, and signal disturbances.
- *Data Loss*: Indirect lightning strikes can corrupt data stored in electronic devices. Hard drives, solid-state drives, and memory cards are vulnerable, as sudden electromagnetic interference or power loss during a strike can lead to file system errors and data fragmentation.
- *Voltage Spikes:* Lightning-induced voltage spikes can occur even if the strike doesn't hit directly. These spikes travel through power lines and can reach connected devices. Sensitive components (such as microchips and transistors) may get damaged by sudden voltage changes.

The evaluation of electromagnetic coupling from indirect strikes has been faced in several papers, analyzing the possible damages inferred to transmission and distribution systems as well as on the renewable energy sources systems (especially PV plants and WT), leading to different models to evaluate the effectiveness of mitigation/protection systems. Due to the complexity of the LE, the most adopted models are the numerical ones, typically divided into *transmission-line* models and *full-wave* models. While the methods belonging to the first category usually require low computational effort, the second ones can model the complete electromagnetic coupling mechanism in soil or air with a higher level of detail.

Present lightning protection standards provide criteria for designing different kinds of Lightning Protection System (LPS), aimed at mitigating the risk associated with LE. LPSs are based on the risk assessment, i.e., on the combination of:

- the number of LE affecting the considered equipment (threat);
- the probability that a LE causes damage (vulnerability);
- the amount of the associated loss (consequence).

The protection from LE is based on the idea that hits are unavoidable due to the random nature of LE, and it is only possible to reduce damages. According to [] and [], four lightning protection levels can be introduced, and the possible protection measures depend on the infrastructure to be protected, but can be summarized as follows:

- Shielding wires (for power delivery and transmission systems);
- Earthing and Bonding measures;
- Surge protective devices;
- Cables shielding.

The choice of the protection system involves three main subsequent phases:

1. the lightning current modeling;
2. the Electro-Magnetic Fields (EMF) modeling;
3. the modeling of the EMF coupling with the infrastructure to be protected, which provides the effective damage inferred to it.

The aim of the FELINES project is to investigate the possibility of measuring the PBP related fields and use these measurements as an early warning to trigger protection systems. As a first step of the project, thoughtful research of bibliography has been performed to identify possible models for the simulation of LE early phases, but also to identify sources of measured data, as the experimental part is out of the scope of FELINES, which mainly relies on simulations of the PBP.

In the remaining of this report, we will briefly analyze the most relevant effects of LE on different types of equipment, highlighting the possible countermeasures presently adopted to mitigate the impact of direct or indirect strikes.

2. Impact on Power delivery and distribution systems

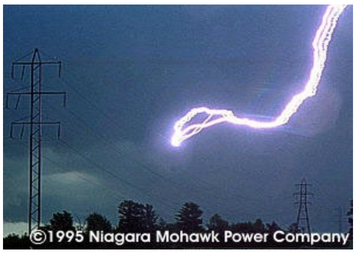
Transmission lines are obviously the most vulnerable component, due to their dimension and geometrical characteristics. The literature in this field is vast, and dates to the seventies or earlier. It is estimated that lightning-related power outages and equipment damage cost utility companies billions of dollars annually. For example, in 2019, lightning-induced outages in North America led to approximately $6 billion in costs due to damaged infrastructure, lost productivity, and repair expenses.

Lightning usually causes temporary faults on overhead distribution lines. If the fault is cleared by a breaker or a recloser, the circuit may be successfully reclosed. In the past this was acceptable, but now with the proliferation of sensitive loads momentary interruptions are a major concern. Power-quality concerns have created more interest in lightning, and improved lightning protection of overhead distribution lines against faults is being considered as a way of reducing the number of momentary interactions and voltage sags.

Lightning may also cause permanent faults. From 5-10% of lightning-caused faults are thought to cause permanent damage to equipment. Temporary faults may also cause permanent interruptions if the fault is cleared by a one-shot protective device, such as a fuse.

Lightning poses a major challenge to power utilities worldwide by inducing damage to infrastructure, causing power outages, and reducing system reliability. The effects of lightning on power distribution lines are multifaceted, impacting both the physical infrastructure and the overall operation of the electrical grid.

Lightning strikes can affect power distribution systems in several ways, primarily through direct strikes and induced overvoltages:



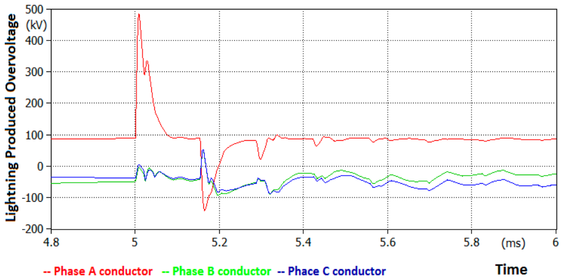
A picture of a Lightning Strike on overhead power transmission line

- **Direct Strikes**:

  When lightning directly hits a power line or associated equipment (such as transformers or substations), it transfers a very large amount of energy into the system. The current from the lightning strike can range from tens to hundreds of kiloamperes (kA), which far exceeds the normal operating current of power distribution systems. This causes physical damage and may result in insulation breakdown, arcing, or catastrophic failure of the electrical equipment.

- **Induced Overvoltages**:

  Even if lightning does not strike a line directly, it can induce high voltages in power lines through electromagnetic coupling. The rapid change in electric fields during a lightning discharge induces transient overvoltages, which propagate along the distribution lines. These transients can exceed the insulation rating of the power lines and equipment, potentially causing damage or tripping protective devices. An example is reported aside.



Produced overvoltage waveforms on power line conductors in case of lightning strike to the upper phase wire (from L. Czumbil et al., "Induced Voltages in Metallic Pipelines due to Lightning Strikes to nearby Power Lines")

- **Grounding-Related Issues**:

  When lightning strikes nearby objects like trees, buildings, or the ground itself, the resulting high ground potential rise can affect the grounding systems of the distribution network. If grounding systems are inadequate or improperly designed, the lightning energy can enter the electrical system, leading to damage or safety hazards.


A lightning strike on a tree, Lutz, Florida (USA), 2019

Types of Damage Caused by Lightning on Power Distribution Systems

1. **Insulation Failure**:

   The excessive voltage caused by lightning can exceed the dielectric strength of insulation materials used in power lines and equipment. This can result in flashover or puncture, damaging insulators and causing short circuits. The breakdown of insulation leads to power outages, line faults, and possible cascading failures in the distribution network.

2. **Equipment Damage**:

   Transformers, circuit breakers, and other critical infrastructure components in substations are vulnerable to lightning strikes. High-energy lightning surges can damage the windings of transformers, render circuit breakers inoperable, and destroy other protection and control equipment. This can lead to prolonged outages and costly repairs.

3. **Arcing and Fires**:

   Direct lightning strikes can create electrical arcs across insulators or between phases of the power line. This arcing may ignite fires on wooden poles, dry vegetation, or other flammable materials near the distribution lines. Wildfires caused by lightning-induced arcing are a significant risk in rural and forested areas, potentially leading to extensive damage and further complicating power restoration.

4. **Voltage Sags, Surges, and Interruptions**:

   Even when physical damage is avoided, lightning-induced voltage transients can cause voltage sags, surges, or temporary interruptions in the power supply. Sensitive electronic equipment, industrial processes, and critical infrastructure may experience malfunction or damage due to these voltage irregularities.

5. **Power Outages and Grid Instability**:

   Lightning strikes often cause line trips or faults, which can lead to partial or complete power outages. Multiple lightning strikes during a storm may cause cascading failures, where several parts of the grid become unstable due to overloaded systems, leading to regional blackouts. Recovery from such events is complex, requiring significant coordination between grid operators and maintenance teams.

Mitigation Strategies

To minimize the effects of lightning on power distribution lines, various protection strategies are employed. These include:

1. **Surge Arresters**:

   Surge arresters are installed at critical points in the distribution network to absorb the high-voltage surges caused by lightning. These devices divert excess energy to the ground, protecting the power lines and equipment from being exposed to damaging voltages. Surge arresters are commonly used in conjunction with transformers, substations, and long stretches of overhead lines.

2. **Shield Wires and Ground Wires**:

   A common method of protecting power lines from direct lightning strikes is by installing shield wires or ground wires above the conductors. These wires intercept lightning strikes and safely direct the current to the ground via properly designed grounding systems. In some regions, these shield wires also double as communication lines.

3. **Proper Grounding Systems**:

   Effective grounding is essential to dissipate the high energy from lightning strikes and induced surges. Grounding systems must be well-designed and maintained to ensure low-resistance pathways for the lightning current. This reduces the risk of equipment damage and ensures that protection devices such as surge arresters can function correctly.

4. **Line Insulators**:

   Special high-voltage insulators are used to prevent flashovers during lightning events. Composite insulators with hydrophobic properties are more resistant to pollution and water, reducing the risk of flashover. These insulators help maintain the dielectric strength of the system even under adverse weather conditions.

5. **Underground Cabling**:

   In areas prone to frequent lightning strikes, underground cables are a more reliable alternative to overhead lines. While more expensive, underground power lines are less susceptible to direct lightning strikes and their associated damage. However, even underground cables can be affected by ground potential rise from nearby strikes, necessitating proper grounding and surge protection.

6. **Lightning Detection and Prediction Systems**:

   Advanced lightning detection systems are used to predict and monitor lightning activity in real time. Power utilities can use this data to reconfigure the grid, isolate sensitive areas, or prepare for quick restoration of service in case of outages. Some utilities also employ automated systems that disconnect vulnerable sections of the grid before lightning strikes occur, minimizing potential damage.

The last mitigation system is the topic of the FELINES research project.

3. Impact on Photovoltaic plants

Photovoltaic (PV) plants are renewable energy systems that generate electricity from sunlight. As these systems become increasingly widespread and essential to the global energy mix, ensuring their reliability is paramount. However, due to their large surface areas and exposure to the outdoors, PV plants are vulnerable to environmental hazards such as lightning strikes.

Lightning strikes can have severe consequences on PV plants, including physical damage to equipment, degradation of system performance, and prolonged downtime. This report examines the impact of lightning on photovoltaic systems, the types of damage it can cause, and the mitigation strategies implemented to reduce these risks.

[Insert image: Lightning near a photovoltaic plant]

Lightning strikes can affect photovoltaic systems in several ways, both through direct strikes and indirect effects:

- **Direct Strikes:**

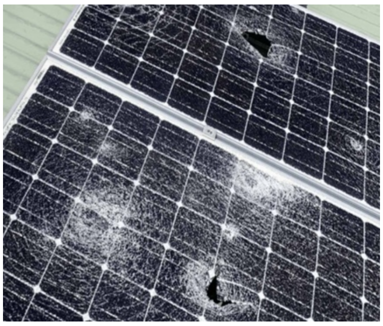
  A direct lightning strike to any component of a PV plant, such as the solar panels, inverters, or mounting structures, can cause catastrophic damage. The high current from the strike generates extreme heat, leading to physical destruction of panels, connectors, and other equipment.

- **Induced Overvoltages:**

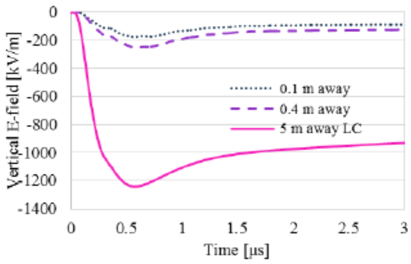
  Even if lightning does not directly strike a PV plant, it can induce overvoltages in the circuitry. These surges can travel through electrical wiring, causing damage to sensitive electronic components such as inverters, charge controllers, and monitoring systems. The electromagnetic field created by nearby lightning can also induce damaging currents in long cable runs.

- **Ground Potential Rise:**

  When lightning strikes the ground near a PV system, the ground potential can rise rapidly, resulting in differential voltages between different parts of the system. This can lead to flashovers or arcing, potentially damaging grounding systems and connected equipment.



A PV panel hit by a lightning strike



Vertical electric field at ground for different positions of a lighting strike (M. A. Hossain and Md. R. Ahmedm Analysis of Indirect Lightning Phenomena on Solar Power Systems, Int. Journ. Of Electrical Engin,, 2014

Types of Damage Caused by Lightning on PV Plants

1. **Solar Panel Damage:**

   Direct lightning strikes can destroy solar modules by burning through the glass, damaging the solar cells, and melting metal connectors. Even nearby strikes can cause microcracks in solar panels, which reduce their efficiency and lifespan.

2. **Inverter Damage**:

   Inverters, which convert DC electricity from the solar panels to AC for grid use, are particularly vulnerable to lightning-induced surges. A high-voltage surge can destroy inverter circuitry, rendering the PV system inoperable until repairs are made.

3. **Damage to Cables and Connectors:**

   The long cables that connect solar panels, inverters, and other components are susceptible to overvoltage damage. High-voltage transients can degrade insulation, cause overheating, or even start fires in extreme cases.

4. **Grounding System Damage:**

   Lightning can raise the potential of the ground, causing breakdowns in the system's grounding network. A compromised grounding system increases the risk of further equipment damage and poses a serious safety hazard.

Effects on Plant Performance and Operations

The damage caused by lightning strikes not only results in costly repairs but can also significantly affect the overall performance and operation of a photovoltaic plant:

1. **Reduced Energy Output:**
   Damaged solar panels and inverters reduce the total energy output of the system. Microcracks in panels or partial failure of an array can lead to inefficient operation, resulting in lower electricity generation.
2. **Extended Downtime**:
   After a lightning strike, PV plants often require inspections, testing, and repairs before they can resume normal operation. This leads to downtime, during which the plant is not generating any electricity, resulting in financial losses.
3. **Monitoring and Communication System Failures:**
   Many modern PV plants are equipped with monitoring systems that track performance in real-time. Lightning strikes can damage these systems, leading to a loss of monitoring capabilities and delayed detection of issues.

Mitigation Strategies

Several strategies are implemented to protect photovoltaic plants from the effects of lightning:

1. **Lightning Protection Systems (LPS):**
   LPS are designed to intercept lightning strikes and safely channel the current into the ground. These systems include lightning rods, conductors, and proper grounding.
2. **Surge Protection Devices (SPDs)**:
   SPDs are installed on critical components such as inverters, transformers, and communication systems to protect them from overvoltage transients. SPDs divert the surge to the ground, preventing damage to sensitive equipment.
3. **Proper Grounding:**
   A robust and well-designed grounding system is essential to dissipate lightning energy safely. Grounding systems must be regularly inspected and maintained to ensure they function correctly.
4. **Shielding and Cable Management:**
   Proper shielding of cables and the use of buried cables where possible can reduce the risk of damage from induced voltages. Burying cables also protects them from direct strikes.
5. **Regular Maintenance and Inspection**:
   Preventive maintenance, including the inspection of surge protection devices, grounding systems, and lightning rods, ensures that the system remains protected from lightning strikes.

4. Impact on Wind turbines and Eolic systems

Wind farms are increasingly becoming a vital part of the global energy mix. However, their tall structures and exposed locations make them particularly vulnerable to lightning strikes. Understanding the effects of lightning on wind farms is crucial for improving their resilience and operational efficiency.

Types of Damage Caused by Lightning on Wind Turbines

1. **Structural Damage**:
   Lightning strikes can cause significant damage to wind turbine blades, nacelles, and other components. The high voltage and current from a strike can led to physical damage, such as cracks and delamination in the blades.
2. **Operational Disruptions**:
   Lightning can disrupt the operation of wind turbines, leading to downtime and loss of energy production. This can result in substantial financial losses for wind farm operators.
3. **Increased Maintenance Costs**:
   Frequent lightning strikes necessitate regular inspections and maintenance, increasing the operational costs of wind farms.

A lightning strike hitting a wind turbine

Mitigation Strategies

1. **Lightning Protection Systems**:
   Installing effective lightning protection systems (LPS) is essential. These systems help to safely channel the lightning current away from critical components, minimizing damage.
2. **Regular Inspections**:
   Conducting regular inspections and maintenance can help identify and repair damage caused by lightning strikes, ensuring the longevity and efficiency of wind turbines.
3. **Advanced Materials**:
   Using advanced materials that are more resistant to lightning damage can also help mitigate the effects. For example, carbon fiber-reinforced blades are being developed to withstand lightning strikes better.

Statistics on Lightning Strikes at Wind Farms

- **Frequency of Strikes**:
  On average, each wind turbine blade can be struck by lightning between 1 to 20 times per year, depending on the location and storm activity.
- **Damage Impact**:
  Lightning damage accounts for approximately 60% of operational blade losses and nearly 20% of overall operational wind losses.
- **Energy Released**:
  The average energy released in a lightning strike is about 55 kWh, but some strikes can be up to 20 times more powerful.
- **Height Factor**:
  Wind turbines, often standing 200 meters or taller, are particularly susceptible to lightning strikes. During storms, they can attract a bolt every three seconds.

5 Impact on buildings and other devices and systems

Impact on Buildings

Lightning can have significant effects on buildings and infrastructure. It occurs due to the buildup of electrical charge in storm clouds, and when this charge is discharged to the ground, it can strike structures, leading to severe damage. This report explores the impact of lightning on buildings, and measures that can be taken to protect against lightning strikes.

Effects of Lightning on Buildings

A lightning strike hitting on buildings

1. **Physical Damage**
   A direct strike can cause significant structural damage to buildings, especially to roofs, walls, and any tall structures. The intense heat generated can melt materials or lead to structural failures.
2. **Electrical Systems**
   Buildings' electrical systems are vulnerable to surges caused by lightning strikes. These surges can damage equipment, lead to system failures, and even cause fires. Sensitive electronics are particularly at risk from indirect strikes.
3. **Fire Hazard**
   Lightning-induced fires can occur when a building's flammable materials are exposed to the extreme heat of a strike. Wood-framed structures are especially vulnerable, though metal buildings are not immune to this hazard.

Secondary Effects

Aside from physical and electrical damage, lightning can also affect plumbing systems, HVAC systems, and other infrastructure. The intense energy from a strike can travel through metal pipes, potentially causing damage or leaks.

Lightning Protection Systems (LPS)

1. **Lightning Rods**
   Lightning rods are designed to intercept lightning strikes and safely conduct the electricity into the ground, preventing damage to the building. They have been used for centuries and remain a cornerstone of lightning protection systems.
2. **Surge Protectors**
   Surge protectors are critical for safeguarding electrical systems. These devices limit the voltage that reaches electrical circuits, preventing damage to sensitive equipment.
3. **Grounding Systems**
   A well-designed grounding system is essential for minimizing the effects of a lightning strike. The system provides a low-resistance path for the electrical current to dissipate safely into the earth.
4. **Faraday Cage Concept**
   The Faraday cage principle can be applied to buildings to shield them from lightning. By surrounding the structure with conductive materials that direct electricity to the ground, the building can be protected from the effects of lightning strikes.

Design Guidelines for Lightning Protection

International standards, such as those from the IEC and NFPA, provide guidelines for designing effective lightning protection systems. These include specifications for the installation of lightning rods, grounding systems, and surge protection devices.

Impact on Power Transformers

Lightning strikes pose a significant threat to power transformers, which are critical components in electrical power systems. This report examines the direct and indirect effects of lightning on power transformers, including the mechanisms of damage and potential mitigation strategies.

Direct Effects

Transformer hit by a direct strike in Roy (UT), Sept. 29th, 2022

1. **Insulation Breakdown**
   When lightning strikes a transformer, the high voltage can exceed the dielectric strength of the insulation materials used in the transformer. This can cause the insulation to break down, leading to short circuits and potential transformer failure.
   Insulation breakdown can result in immediate transformer failure, requiring costly repairs or replacements. It can also lead to prolonged power outages and reduced reliability of the power grid.
2. **Thermal Damage**
   The immense energy from a lightning strike generates intense heat. This heat can cause the conductors within the transformer to melt or deform. Thermal damage can lead to the destruction of transformer windings and other internal components. This not only affects the transformer's performance but can also pose safety hazards such as fires.
3. **Mechanical Stress**
   The rapid expansion of air and materials due to the heat from a lightning strike can create significant mechanical forces. These forces can deform or even rupture transformer components[1]. Mechanical stress can cause physical damage to the transformer housing and internal structures. This can lead to oil leaks, structural failures, and increased maintenance costs.
4. **High Return Stroke Peak Current**
   Lightning strikes often involve high peak currents, which can induce large electromagnetic forces within the transformer. These forces can cause vibrations and mechanical stresses that may damage the windings and core of the transformer. Over time, this can degrade the transformer's performance and lifespan[1].
5. **Multiple Flashes and Positive Lightning Flashes**
   Multiple lightning flashes or positive lightning flashes, which carry more charge and energy, can cause repeated or more severe impacts on the transformer[1]. Repeated exposure to high-energy lightning strikes can accelerate the aging of transformer insulation and other components, leading to premature failure[1].

Indirect Effects

Even without a direct strike, lightning can induce significant electrical disturbances:

1. **Electromagnetic Pulses (EMP)**:
   Lightning generates EMPs that can induce high voltages and currents in nearby power lines, leading to overvoltages in transformers.
2. **Transient Overvoltages**:
   These overvoltages can stress the insulation system of transformers, potentially leading to dielectric failure over time.
3. **Resonance Stresses**:
   Studies have shown that lightning impulses can cause resonance stresses in high voltage transformers, leading to overvoltages and potential damage.

Mitigation Strategies

To protect transformers from lightning-induced damage, several strategies can be employed:

1. **Surge Arresters**:
   Installing surge arresters can help to divert lightning-induced overvoltages away from transformers.
2. **Shielding and Grounding**:
   Proper shielding and grounding of transformers and associated infrastructure can reduce the impact of electromagnetic pulses.
3. **Regular Maintenance and Monitoring**:
   Regular inspection and maintenance of transformers, along with on-line monitoring systems, can help to detect and mitigate potential issues before they lead to failure.

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