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Ilham DEBIH

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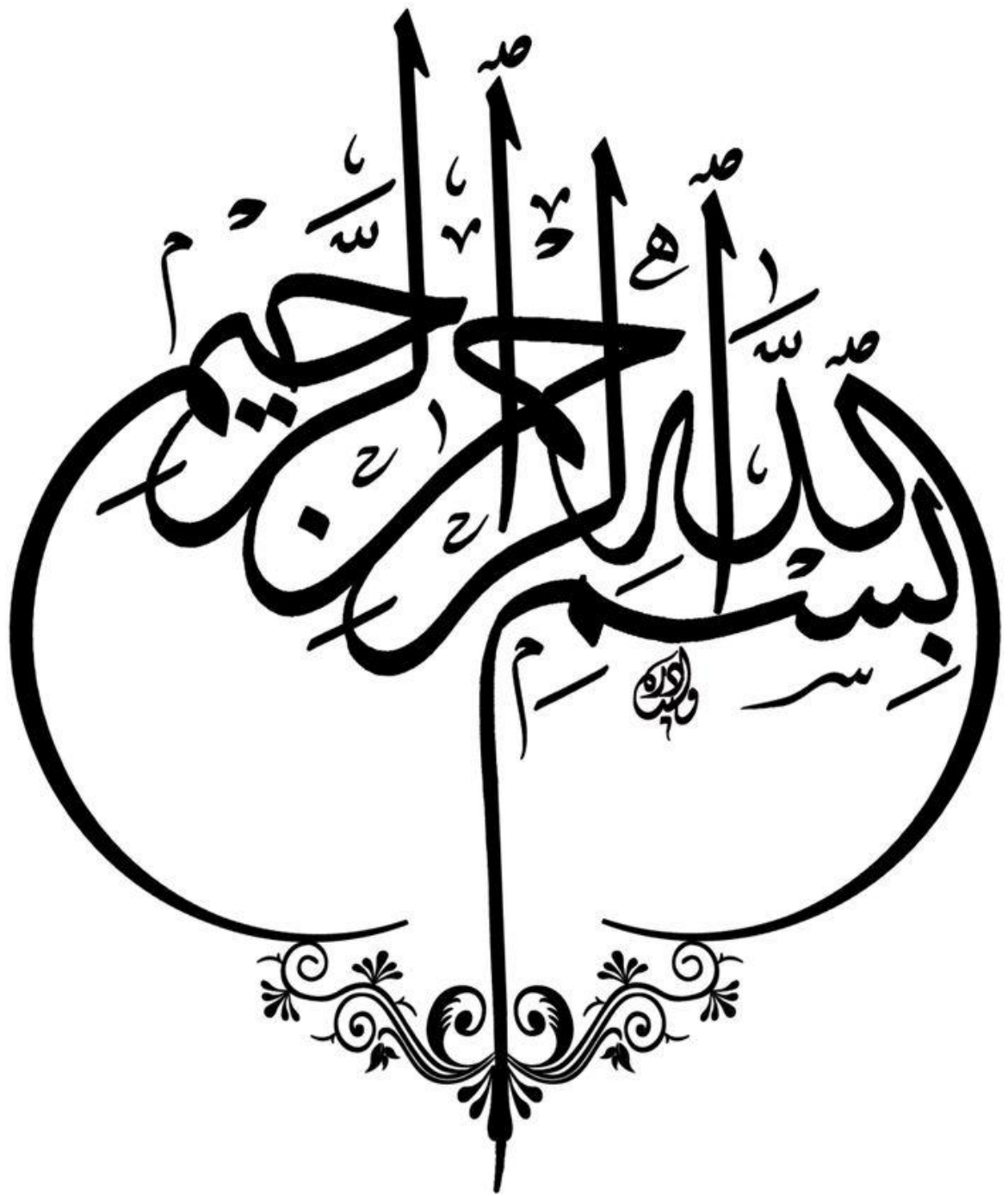
**Analysis of insulator strings under degraded
conditions: New perspectives for performance
assessment**

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Defended in front of the jury composed of:

First and last name	Grade	Establishment	Quality
CHOUDER Aissa	Professor	University of M'sila	President
BAKRI Badis	Associate professor "A"	University of M'sila	Supervisor
BENGUESMIA Hani	Professor	University of M'sila	Co-Supervisor
BELHITECHE El'hadi	Associate professor "B"	University of M'sila	Examiner

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إهداء

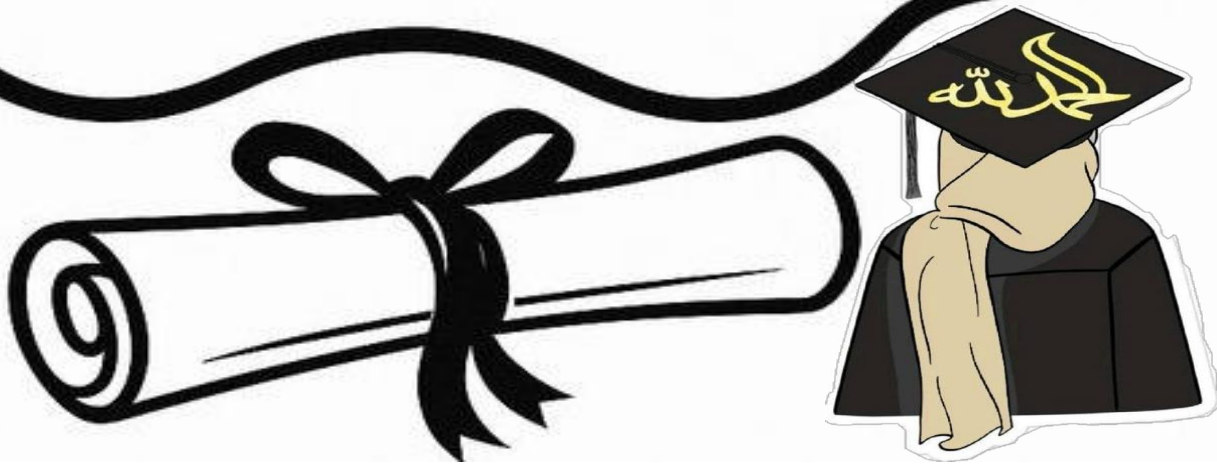
أهدي ثمرة نجاحي، ونتيجة رحلتي، إلى من قال فيهما الله تعالى هذه الآية الكريمة "وَقَضَىٰ رَبُّكَ أَلَّا تَعْبُدُوا إِلَّا إِيَّاهُ وَبِالْوَالِدَيْنِ إِحْسَانًا "

إلى قدوتي الأولى، أمي الحبيبة، إلى معنى الحنان وصدق العطاء، إلى من كان دعاؤها سر توفيقتي، إليك يا من لم تشتكي يوماً، وتحملت بصمت، ورافقتني في كل تفاصيل حياتي. كنت الحزن والملجأ. اللهم احفظها لي، وارزقها العفو والعافية، وأكرمها بالفرح والأمل، فإنها جنتي في الدنيا، ونور دربي إلى الآخرة.

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إلى إخوتي الأعزاء، شركاء الطفولة، ومصدر القوة في حياتي. وجودكم وحده كان كافياً ليشعرني بالأمان، فشكراً لكم من القلب .

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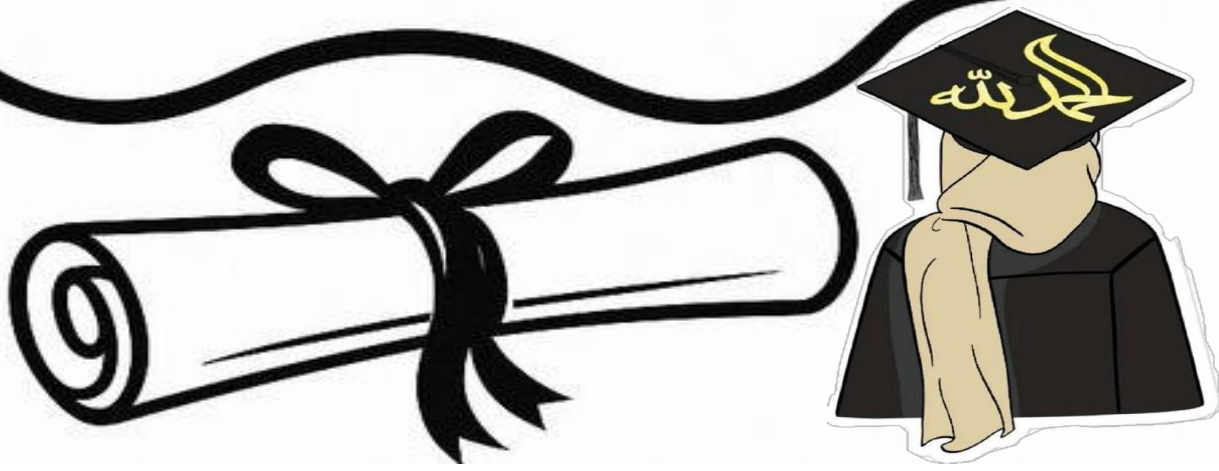
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I dedicate the fruit of my success and the result of my journey to those mentioned in the words of Allah: "**And your Lord has decreed that you not worship except Him, and to parents, good treatment**"

To my first role model, **my beloved mother** the true meaning of kindness and giving. Your prayers were the secret of my success, and your love healed my pain. You never complained, you stayed strong in silence, and stood by me in every step of my life. You were my shelter and safe place. May Allah protect you for me, bless you with health and mercy, and grant you the highest level of Paradise. You are my heaven in this world and the light that guides me to the next.

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To everyone who crossed my path and left a kind mark on my heart
This achievement is not mine alone it is the result of your support, love, and prayers.

To all of you, I offer this dedication from the depths of my heart.

DEBIH Ilham



شكر وتقدير

**** (يَرْفَعُ اللَّهُ الَّذِينَ آمَنُوا مِنْكُمْ وَالَّذِينَ أُوتُوا الْعِلْمَ دَرَجَاتٍ) ****

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تُعد العوازل ذات الجهد العالي عناصر أساسية في أنظمة نقل الطاقة الكهربائية، إذ تؤمن الدعم الميكانيكي والعزل الكهربائي للموصلات. يهدف هذا العمل إلى دراسة السلوك الكهربائي لعازل زجاجي من نوع L1512 في حالة وجود تلف أو كسر. تم استخدام محاكاة ثلاثية الأبعاد عبر برنامج COMSOL Multiphysics، حيث تم تمثيل حالات ضرر مختلفة في أعلى ووسط وأسفل العازل لتحليل توزيع الجهد والمجال الكهربائي. يساهم هذا العمل في توضيح تأثير موقع الضرر على الإجهاد الكهربائي خلال ظروف التشغيل.

الكلمات المفتاحية: العازل، ضرر، المجال الكهربائي، توزيع الجهد، COMSOL Multiphysics، محاكاة ثلاثية الأبعاد.

Abstract

High voltage insulators are critical components in power transmission systems. They provide both mechanical support and electrical insulation for energized conductors. This study focuses on evaluating the electrical behavior of a 1512L glass insulator affected by damage or fracture. The analysis is performed using a three-dimensional simulation approach with COMSOL Multiphysics. The model considers different damage locations (top, middle, bottom) along the insulator body to study their influence on the electric potential and field distribution. The work contributes to understanding how damage location may influence the electrical stress on the insulator under service conditions.

Keywords: Insulator, damage, electric field, potential distribution, COMSOL Multiphysics, 3D simulation.

Résumé

Les isolateurs à haute tension sont des composants essentiels des réseaux de transport d'électricité. Ils assurent à la fois un soutien mécanique et une isolation électrique. Ce travail porte sur l'analyse du comportement électrique d'un isolateur en verre de type 1512L en présence de dommages ou de fractures. Une modélisation tridimensionnelle a été réalisée à l'aide du logiciel COMSOL Multiphysics, en considérant plusieurs positions de dommage (haut, milieu, bas) afin d'étudier leur effet sur la distribution du champ électrique et du potentiel. L'étude vise à comprendre comment la localisation du dommage peut influencer les contraintes électriques en conditions de service.

Mots-clés: Isolateur, dommage, champ électrique, distribution du potentiel, COMSOL Multiphysics, simulation 3D.



" List of abbreviations and symbols"

List of abbreviations and symbols

L	Level of pollution
FEM	Finite Element Method
LC	Leakage current
HV	High voltage
σ	Conductivity (mS/cm ²)
DC	Direct current
V	Electric potential(V)
E	Electric field(V/m)
ϵ	Absolute permittivity
ϵ_0	Permittivity of free space
ϵ_r	Relative permittivity
ρ	The charge density
GUI	Graphical user interface
FEA	FiniteElementAnalysis
k	Kilo
v	Voltage
m	Meter
mm	Millimeter
cm	Centimeter
mS	Milli siemens
μm	Micrometer
S	Siemens
N	Newton
g	Gram
A	Ampere



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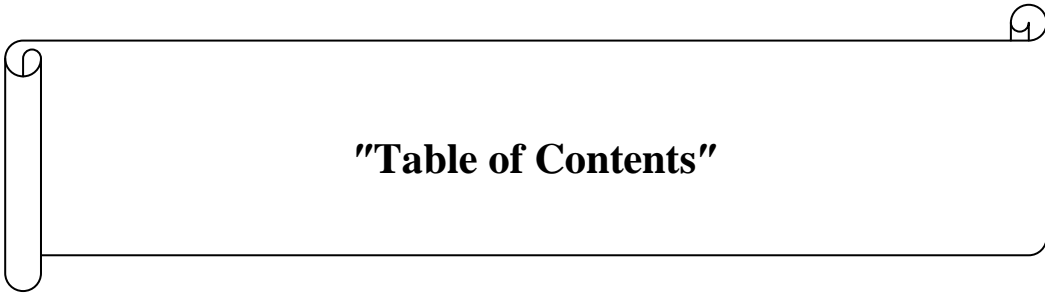
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"General Introduction"

General introduction

The generation, transmission, and distribution of electrical energy form the backbone of the economy of a modern industrial state. With the advancement of industrialization, increasingly high demands are placed on the availability of this energy. For economic reasons, the transmission and distribution of electrical energy are generally carried out through overhead lines. The reliability of these lines therefore depends significantly on the mechanical, electrical, and dielectric behavior of their various components. Among these components, insulators play a critical role, making their selection of utmost importance.[1]

The performance and weather resistance of insulators have been improved over time through manufacturing innovations. Insulators are essential to preserving a consistent energy supply because disruptions are a big worry. They play a crucial part in establishing electrical insulation between grounded and high voltage components, which highlights their importance for the dependability of the electrical energy transmission system.[2]

Additionally, the high-voltage overhead wires, which traverse a variety of areas and climates and carry electrical energy, expose these systems to a number of challenges, most notably the problem of insulator pollution. While pollution significantly threatens the reliability and quality of power supply by reducing insulation performance, an even more critical and hazardous issue is insulator damage. Mechanical damage, such as cracking or structural failure whether due to aging, environmental stress, or manufacturing defects can lead to immediate and severe consequences such as flashovers, line outages, or even permanent damage to network components. Unlike pollution, which typically has progressive and predictable effects[3], insulator damage can result in sudden and catastrophic failures, making it a central concern in the design, maintenance, and reliability assessment of high-voltage networks. Consequently, this dissertation focuses primarily on the impact of insulator damage and its implications for the integrity of overhead transmission lines.

This research aims to investigate the distribution of electric field and potential along a high-voltage glass cap-and-pin insulator subjected to mechanical damage. Given the difficulty of accurately measuring these distributions in real-world conditions, a numerical simulation approach based on the finite element method (FEM) was adopted using COMSOL Multiphysics.[4]

The study examines three specific damage scenarios in the insulator string: upper, lower, and middle damage.

The thesis opens with a comprehensive overview of high-voltage insulators, emphasizing their vital role in maintaining the reliability of power transmission systems, particularly under severe environmental and mechanical conditions. The first chapter reviews previous research, discusses different insulator types and structures, and highlights key challenges such as pollution and mechanical damage.

Next, we enter the field of computer simulations, where we will create a simulated testing environment to investigate the behavior of insulators using the capabilities of COMSOL Multiphysics. We investigate scenarios in three dimensions, concentrating especially on the electrostatic components.

In the final chapter, 3D simulation results for each damage scenario upper, middle, and lower locations are presented and analyzed.

Finally, we present a general conclusion of this work and the outlook suggested by this study.

Chapter I

"Insulators In Power Transmission Systems"

I.1. Introduction

In electrical power transmission systems, insulation plays a crucial role in connecting conductors to supports while ensuring their electrical isolation.[5]

However, due to prolonged exposure to diverse environmental conditions, mechanical stresses, and electrical loads, insulators are susceptible to degradation over time. Understanding this degradation process is essential for maintaining the reliability and safety of electrical infrastructure. Changes to an insulator's surface can alter its electrical properties, increasing the risk of flashovers and potential power disruptions. Pollution is a significant concern as it accelerates aging and reduces insulator performance.[2]

This chapter explores the key electrical and mechanical properties of insulators, examines the primary factors contributing to their deterioration, and evaluates the impact of degradation on their performance. By establishing a solid foundation in insulator fundamentals and incorporating case studies, this section illustrates these critical concepts.

I.2. Insulators

The insulator shown in Figure I.1 is a specialized component fabricated from solid insulating material, designed to withstand electrical stress. It exhibits high impedance, effectively blocking the flow of electric current. Its primary function is to provide electrical isolation between two conductive elements at different potentials.[5]



Figure I.1. High-voltage insulator.

I.3. Function and structure of an insulators

In the design of high voltage insulators, several insulating rings are stacked and connected together by metal rods. Insulating rings are used to create an electrical barrier between the high

voltage conductor and the supporting structure in order to prevent the passage of electrical current.

The metal rods ensure the mechanical rigidity of the insulator. Insulators usually have two functioning roles: [6]

I.3.1. Mechanical role

The high-voltage insulator serves a critical mechanical function by supporting and suspending the electrical conductor. The **pin** (attached to the conductor) and the **cap** (mounted on the support structure) work together to maintain the conductor at a safe distance from the tower or support structure.

This ensures mechanical stability and prevents contact, safeguarding the integrity of the power transmission system.

I.3.2. Electrical role

High-voltage insulators serve a critical electrical function in power transmission systems. Their primary role is to ensure reliable electrical insulation between high-voltage conductors and their supporting structures (e.g., towers), preventing current leakage and maintaining system integrity.

I.4. Type of insulators

Insulators are divided and classified into different types due to:

I.4.1. Material composition

The primary types of insulators used in transmission lines (shown in Figure I.2) include:

✚ Glass insulators

Glass insulators are extensively utilized, particularly for overhead lines operating at high and medium voltages, owing to their economical production and durability.

Initially, these insulators were crafted from standard glass, which possesses inferior electrical and mechanical characteristics, resulting in a lower voltage capacity and increased fragility compared to toughened glass.

With the advent of toughened glass, the production of glass insulators transitioned to this more resilient material, which can withstand five to six times the electrical and mechanical stress that standard glass can endure.[7]

Porcelain insulators

Porcelain is a well-recognized term associated with high-quality ceramics, as it exhibits lower absorbency compared to traditional ceramics, enabling it to endure greater moisture levels and more severe weather conditions. The enhancement in the quality of insulators is accompanied by a notable rise in production costs.[7]

For insulators designed for environments subject to extreme mechanical stresses, ceramics with exceptionally fine grains are typically favored. Ceramics are commonly utilized in substations, including support insulators, voltage transformers, and power transformer crossing terminals.[1]

Composite insulators

Synthetic insulators, also known as composite insulators, are constructed with a core of fiberglass that is saturated with resin, providing the necessary mechanical strength, and an outer layer made from synthetic insulating materials.

These insulators are advantageous due to their lightweight nature and robust mechanical resistance. They are suitable for use in highly polluted environments and exhibit excellent hydrophobic properties.

However, a notable disadvantage in their application is that they undergo aging due to various stressors, such as electrical, mechanical, and atmospheric influences.[8]

Ceramic insulators

Ceramic insulators are valued for their unique properties, including hydrophilic surfaces that allow water to flow off easily. They possess high dielectric strength, enabling them to withstand high voltages and prevent electrical arcing.

With low electrical conductivity, they reduce current flow, minimizing power losses and accidents.

Their high thermal stability makes them suitable for fluctuating temperatures, and their corrosion resistance extends their lifespan in harsh conditions. Mechanically strong, they support electrical components and endure environmental stresses.

Overall, ceramic insulators are known for their longevity, reliability, and resistance to tracking, ensuring stable performance under challenging conditions.[9]

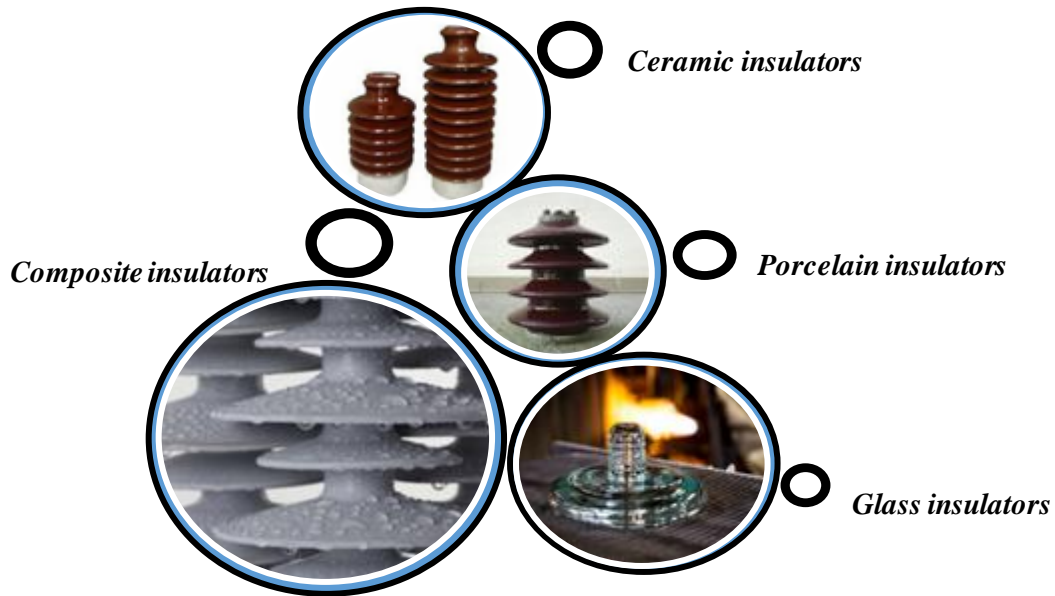


Figure I.2. Insulators types by material.

I.4.2. By functional use

Insulators are classified according to their operational function in electrical systems. Each design meets specific mechanical and electrical requirements for power transmission and distribution networks, including:

✚ Disc insulators

Disc insulators are a type of insulator primarily used in transmission lines. As the name suggests, they are designed in the shape of a disc and are typically assembled in a chain, depending on the service voltage. These insulators are also known as **cap and pin insulators**, as illustrated in Figure I.3.

They consist of three main parts: the cap, the pin, the insulating component, and the patching or fastening part.[6]

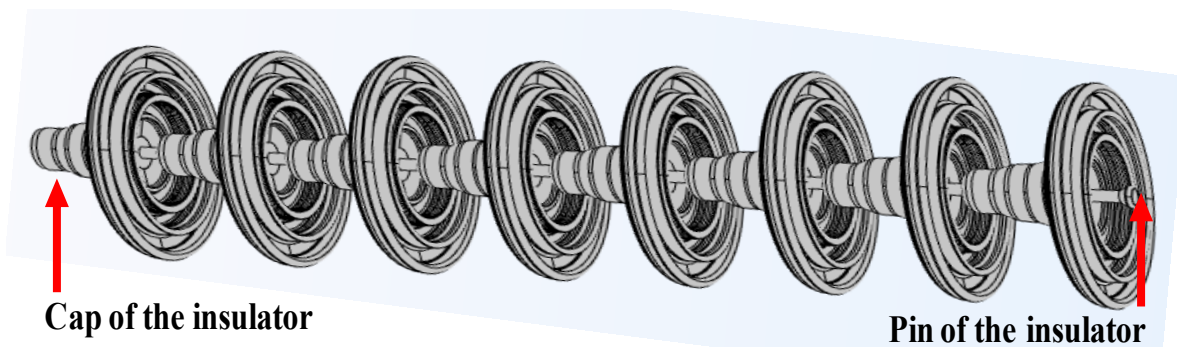


Figure I.3. Cap and pin insulators.

- **Cap and pin:** Metallic parts that connect the pole to the high-voltage cable.
- **Insulation part:** Made of glass or porcelain, it separates the pole from the cable electrically.
- **Patching part:** Holds the insulator together while also providing insulation.

✚ Long rod insulators

Also known as a long-rod insulator, (shown in Figure I.4), this chain element consists of a single elongated a single, elongated insulating element, usually made of porcelain or composite. It is attached to the supporting structure by a metal rod.[10]

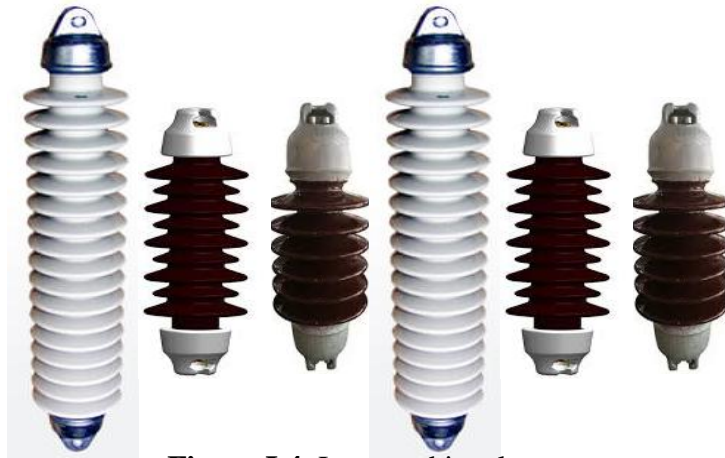


Figure I.4. Long rod insulator.

✚ Strain insulators

Strain-type insulators shown in Figure I.5 are used in transmission lines at dead ends, sharp turns, river or valley crossings, and high-tension points. For high-voltage lines, they consist of suspension-type insulator assemblies with high dielectric and mechanical strength. In extreme tension cases, such as river crossings, two to four parallel strings are used. The insulator discs are arranged vertically, and these insulators are also known as tension insulators.

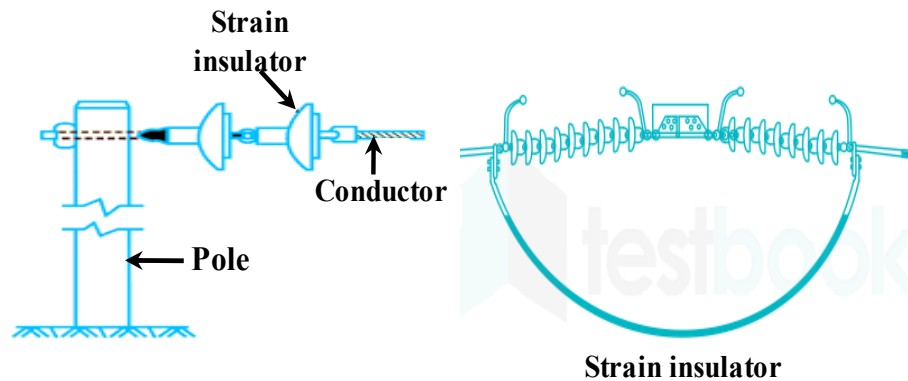


Figure I.5. Strain insulators.

✚ Shackle insulators

In early applications, shackle insulators served as strain insulators. Nowadays, they are primarily used in low-voltage distribution lines (shown in Figure I.6). These versatile insulators can be installed in either horizontal or vertical orientations, and are secured directly to poles with bolts or to cross arms. [9]

The insulator design incorporates a tapered aperture that optimizes load force distribution, significantly reducing fracture risk under full load conditions. However, their usage has declined in recent years due to the widespread adoption of underground distribution systems.



Figure I.6. Shackle insulators.

I.4.3. By installation method

Different types of insulators are used based on their installation method:

✚ Suspension insulators

These kinds of insulators are typically employed as conductor-carrying insulators to safeguard overhead power lines, as shown in Figure I.7. In towers, suspension insulators are frequently made of porcelain or glass materials. They have a string-like form because several insulators are connected in series.[10]

The suspension insulator is hung below the cross arms of the supporting pole, with the line conductor attached to its lower end. Since there is no pin-related issue, the distance between the cross arms and the conductor can be adjusted by varying the number of discs. The entire unit is referred to as a suspension string. The number of discs used depends on factors such as the working voltage, weather conditions, transmission line construction, and insulator size.

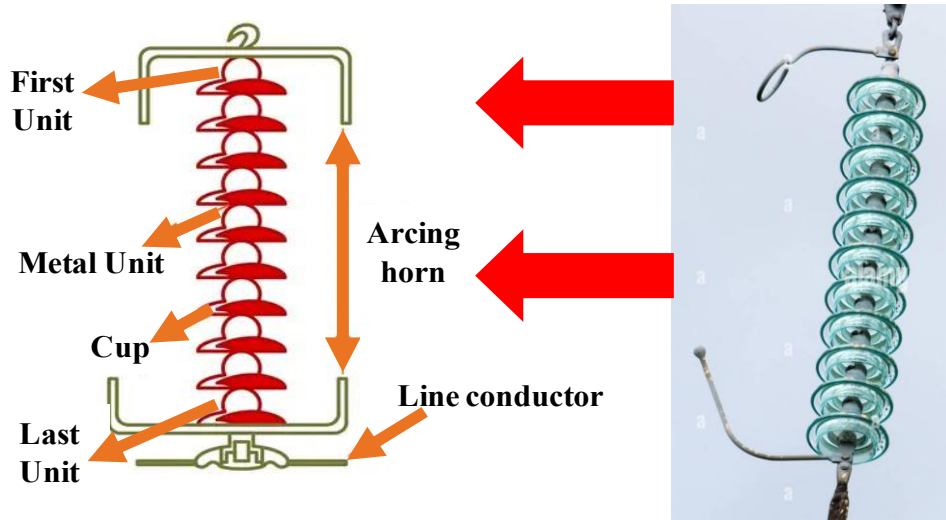


Figure I.7. Suspension insulators.

✚ Pin insulators

Power distribution lines are where you will typically find pin insulators. It is a piece of equipment that shields a wire from external supports like a pin (a wooden or metal dowel) on a utility pole. It is a single-layer shape constructed of porcelain or glass as shown in Figure I.8, two non-conducting materials.

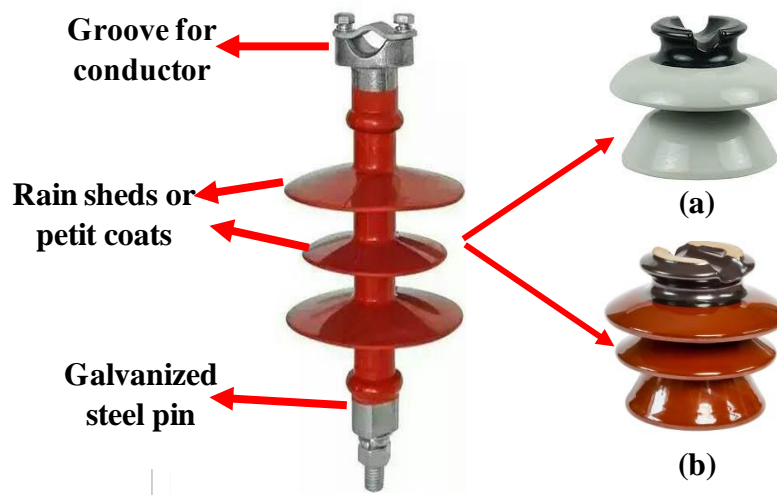


Figure I.8. Pin insulators: (a) Porcelain, (b) Ceramic.

Depending on the voltage application, one or more pin insulators can be used on a physical support. The pin insulator is made of a material with a high mechanical strength and can withstand voltages of up to 11 kV. These can be set up either vertically or horizontally.[6]

✚ Post insulators

Insulators are essential for the safe and stable distribution of electricity generated at power plants (see Figure I.9).

- Post Insulators are similar to pin-type insulators but are specifically designed for high-voltage insulation in substations or power generation facilities. They ensure secure and reliable electricity distribution from power plants.
- These insulators can withstand voltages up to 1100 kV and are typically made of ceramic material or a single piece of composite material (silicone rubber).
- Due to their superior mechanical strength, post insulators are commonly used to protect transformers, switchgear, and other connected equipment.[11]



Figure I.9. Post insulators.

✚ Stay insulators

Stay insulators, also known as strain or guy insulators, feature an egg-shaped design and are used in guy cables to insulate the lower section from the pole, ensuring safety.

- Made of porcelain, they have two drilled holes at right angles for securing guy wires, which loop through both ends (see Figure I.10);
- Typically installed 3 meters above ground level;
- Their size depends on the tensile strength of the guy wire, ensuring both mechanical stability and electrical insulation.[12]

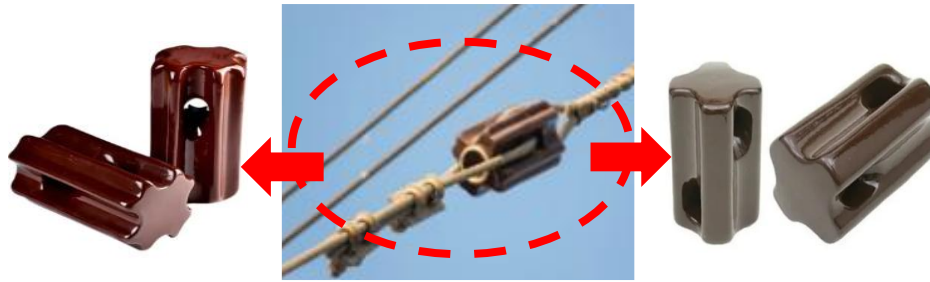


Figure I.10. Stay insulators.

I.5. Profile of insulator

Figure I.11 illustrates various profiles of cap and rod insulators, which are critical components in overhead transmission and distribution systems. These insulators are designed with different shapes and configurations to accommodate varying mechanical loads, voltage requirements, and environmental conditions.

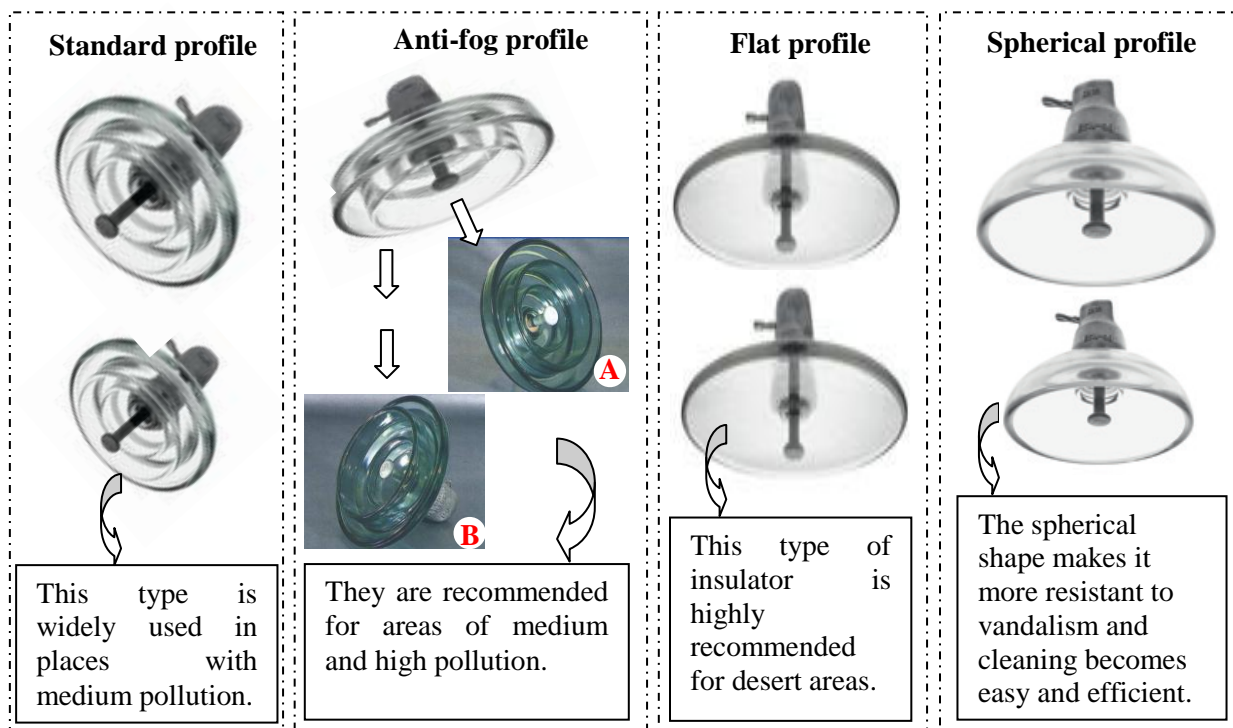


Figure I.11. Différents profils des isolateurs à capot et tige.

I.6. Insulator properties

Electrical insulators are characterized by a set of critical properties that determine their performance and suitability for power system applications. These properties ensure safe, reliable, and long-term operation under varying electrical, mechanical, and environmental conditions.

I.6.1. Electrical properties of insulators

The electrical properties of insulators are critical for ensuring safe and reliable power system operation, as illustrated in Figure I.12:

✚ Leakage current (LC)

The small, undesired current that flows along the surface of an insulator due to contamination, moisture, or material deterioration, compromising insulation efficiency and potentially leading to power losses or equipment damage.

✚ Creepage distance (Leakage distance)

The shortest path along an insulator's surface between two conductive parts, designed to prevent surface current leakage.

✚ Dry arcing distance

The shortest air gap between exposed conductive parts under dry conditions, critical for preventing air breakdown.

✚ Perforation distance

The thickness of insulating material between electrodes, determining resistance to internal puncture under high voltage.

✚ Flashover voltage

The voltage at which a discharge occurs over the insulator's surface (via air or pollution), causing a short circuit.

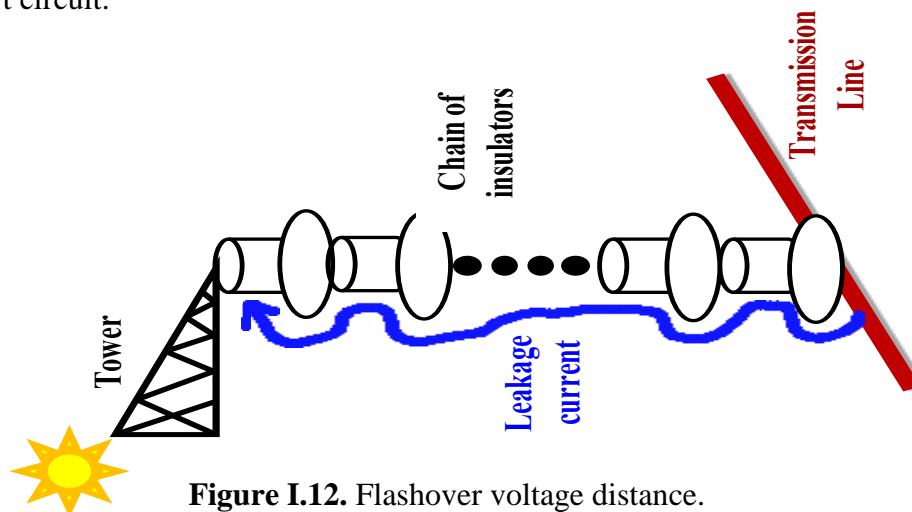


Figure I.12. Flashover voltage distance.

I.6.2. Mechanical load-bearing capabilities of insulators

High-voltage insulators must support mechanical loads while maintaining electrical insulation for ensuring the stability and reliability of the transmission network. The mechanical performance is dependent on:

- ✚ **Tensile strength:** the capacity to endure pulling forces from conductors.
- ✚ **Flexural strength:** which indicates resistance to bending forces.
- ✚ **Impact resistance:** denoting the capability to absorb mechanical shocks without cracking.

Insulators are often exposed to wind forces, ice loads, and vibrations, which must be considered in their design.

I.7. Choice of insulators

Despite representing only 7% of the cost of medium-voltage overhead lines, insulators are crucial for ensuring safety, service quality, and continuity.

Optimal insulators combine self-cleaning properties (minimizing pollutant buildup) with resilience to electrical and mechanical stresses which can escalate unexpectedly under harsh environmental conditions.[11]

I.8. Insulator faults

Cap and pin insulators, which have been widely used in overhead transmission lines, have shown several issues over time, such as erosion, surface tracking, and corona discharge. These problems have been gradually reduced through the improvement of raw materials and the advancement of manufacturing processes.

However, a major challenge with cap and pin insulators remains: the difficulty in identifying faulty units among a string of insulators in service. This necessitates the development of reliable diagnostic methods to distinguish between defective and healthy insulators.

Two main types of defects can be observed in these insulators: electrical and mechanical, and these two types are often interdependent.[12]

I.8.1. Electrical faults

Glass insulators, widely used in overhead transmission lines, are susceptible to aging and surface degradation over time. Environmental factors such as ultraviolet (UV) radiation, pollution, and moisture contribute to the deterioration of the glass surface, leading to the

formation of microcracks and increased surface roughness. These imperfections can compromise the hydrophobic properties of the insulator, facilitating the accumulation of contaminants and moisture. As a result, the risk of surface tracking and electrical discharges increases, potentially leading to flashovers and insulation failure.

Monitoring the aging condition of glass insulators is crucial for maintaining the reliability of power systems. Advanced diagnostic techniques, such as infrared thermography, have been employed to detect invisible damages and assess the pollution level on the insulator surface, enabling timely maintenance and replacement decisions.[13]

I.8.2. Mechanical faults

Mechanical failure can originate from corrosion of the pin that eventually breaks because of the resulting excessive stress. Pin corrosion occurs in highly polluted environments because of dry band arcing around the pin. Metal fitting corrosion may be reduced by the addition of sacrificial zinc rings or sleeves around the pin and/or the cap.[14]

I.9. Destruction

Destruction occurs due to mechanical impacts such as stone-throwing or bullet hits, which cause significant damage to the insulator, including fractures that compromise its integrity.[1]

I.10. Aging of insulating materials

In electrical engineering, electrical ageing is defined as any change in material properties that affect its insulating functions. It can therefore be a chemical or physical change which induces a modification of the electrical properties in a direction unfavorable to the durability of the insulating functions.

It is generally accepted intuitively, and this is often borne out by experience, that the service life of an insulating material depends on the intensity of the electrical stress but also, on the duration of application of this stress.[1]

Under the effect of electrical stress, climatic conditions and pollution, several let's briefly describe them:

I.10.1.Chalking

Appearance of filler particles on the surface of the synthetic material, forming a rough or powdery surface.

I.10.2.Crazecracking

Fine, superficial micro-cracks appearing on the surface of insulating materials, typically ranging from 0.01 to 0.1 mm in depth. These cracks do not necessarily penetrate deeply but indicate initial stages of mechanical degradation.[15]

I.10.3.Cracking

Deeper surface fractures exceeding 0.1 mm in depth, representing more advanced mechanical damage that can jeopardize insulation integrity.[15]

I.10.4.Erosion

Irreversible material degradation characterized by surface loss of material. Erosion can be uniform, localized, or tree-like (arborescent). It is often caused by partial discharges and leads to permanent damage to the insulator's surface.[15]

I.10.5.Tracking

Is an irreversible degradation process where electrically conductive paths are formed on the surface of an insulating material due to electrical discharges in the presence of contaminants and moisture. These carbonized tracks reduce the insulating properties and can ultimately lead to dielectric breakdown.[15]

I.11. Pollution on high-voltage insulators

The most common pollution affecting HV insulators occurs when contaminants accumulate on their surfaces, particularly in industrial or coastal areas. When exposed to moisture such as rain or fog these pollutants can form a conductive layer, leading to leakage currents and potential flashovers.

The pollution on insulators varies in uniformity and distribution, depending on factors like pollutant type, insulators shape, wind, rain, orientation (vertical, horizontal, or inclined), site pollution levels, and their position within the insulators string.[16]

A severe scenario occurs when pollution deposits on damaged insulators, as cracks or surface defects trap contaminants more easily, further degrading electrical performance. This can lead to the formation of electric arcs along the insulating surface, potentially resulting in a complete flashover across the insulator, as illustrated in Figure I.12.[16]

Over time, these effects accelerate aging and raise the risk of total insulator failure, underscoring the importance of regular maintenance and pollution-resistant designs.



Figure I.13. Flashover high-voltage insulators.

I.12. Effects of surface defects on insulator reliability

Surface defects in insulators, such as on damaged surfaces, racks, or erosion, significantly degrade their electrical and mechanical performance. These imperfections create localized stress concentrations, promote contamination accumulation, and facilitate leakage current paths increasing the risk of partial discharges and flashovers.

Over time, such defects accelerate aging, reduce dielectric strength, and compromise long-term reliability, necessitating rigorous inspection and defect mitigation strategies in high-voltage systems.

Damaged insulator surfaces (destroyed, cracks, or erosion) create localized weak points that distort electric fields and trap pollutants, leading to intense partial discharges and tracking. Polluted surfaces, however, form conductive layers when wet, causing widespread leakage currents and flashovers.

While both are critical, damaged surfaces are more dangerous, they accelerate failure unpredictably by combining mechanical weakness with concentrated electrical stress, whereas pollution effects are often gradual and manageable through cleaning. A damaged insulator in a polluted environment poses the highest risk of catastrophic failure.

I.13. Conclusion

This chapter presented a comprehensive overview of high-voltage insulators, emphasizing their critical role in electrical power transmission systems.

Insulators serve dual mechanical and electrical functions, ensuring conductors remain securely supported while maintaining electrical isolation.

The discussion highlighted the detrimental effects of pollution and surface defects on insulator performance. Contamination and physical damage can lead to leakage currents, partial discharges, and flashovers, significantly compromising system reliability. Notably, damaged surfaces pose a greater risk than pollution alone, as cracks and erosion create localized stress points that accelerate failure. A damaged insulator in a polluted environment presents the highest risk of catastrophic failure.

Given these risks, this study focuses on assessing outdoor insulators under destroyed (damaged) conditions to evaluate their performance degradation. The foundational knowledge established in this chapter sets the stage for further analysis of insulators in subsequent sections.

Chapter II

"Numerical Analysis of Damaged Insulators"

II.1. Introduction

With the challenges reviewed in the first chapter about the impact of contamination and surface defects on the performance of dielectrics, it becomes necessary to further analyze how these damages affect the electrical properties of the dielectric.

Surface deterioration does not merely alter the physical appearance of the insulator, but it also causes critical changes in the distribution of electric fields, which can accelerate aging and increase the probability of failure under high-voltage stress.

The introduction of simulation has significantly improved the analysis of high-voltage insulators for overhead lines by using complex models and algorithms to study their behavior. Simulations allow detailed examination of electric fields and potentials, helping to identify stress points, flaws, and optimal performance areas in insulator design.

Electric field distribution is key to understanding insulator behavior under electrical stress. Simulations visualize these fields, revealing critical stress zones and potential failure points that physical inspections might miss. While electric potential distribution also matters, electric field analysis provides deeper insights into early dielectric failure, helping engineers enhance insulator reliability.[17]

In this chapter, we will analyze the performance of high-voltage insulators using simulations conducted in Comsol Multiphysics.

This study investigates the effects of damage on insulators, examining upper, middle, and lower damage regions using three-dimensional (3D) simulations.

These simulations aim to investigate how damage influences the electric field and potential distribution in insulators and assess the resulting impact on their performance under high-voltage conditions.

II.2. Failure causes in high-voltage insulators (Degradation mechanisms of electrical insulators)

High-voltage insulators are critical components in electrical power systems, designed to withstand mechanical loads and electrical stresses while preventing current leakage. However, they can degrade or fail due to various mechanisms.

Below are the primary causes of failure in high-voltage insulators:[1]

- ✚ Electrical failures involve partial discharge, flashover, and tracking, where high voltages cause surface erosion or complete breakdown,
- ✚ Pollution and moisture form conductive layers, leading to flashovers, while UV radiation and chemical exposure degrade polymer insulators,
- ✚ Mechanical stresses like cracking, fatigue, or improper installation weaken structural integrity,
- ✚ Thermal cycling induces material expansion and contraction, accelerating aging.

This work analyzes a damaged chain insulator, specifically the destruction of its fins (Figure II.1), which reduces the leakage distance. This degradation significantly impacts the potential and electric field distribution along the insulator.

The origins of this damage are:

- ✚ Stone and bullet blasts for porcelain and glass insulators.
- ✚ Damage to silicone fin tips caused by bird spikes.

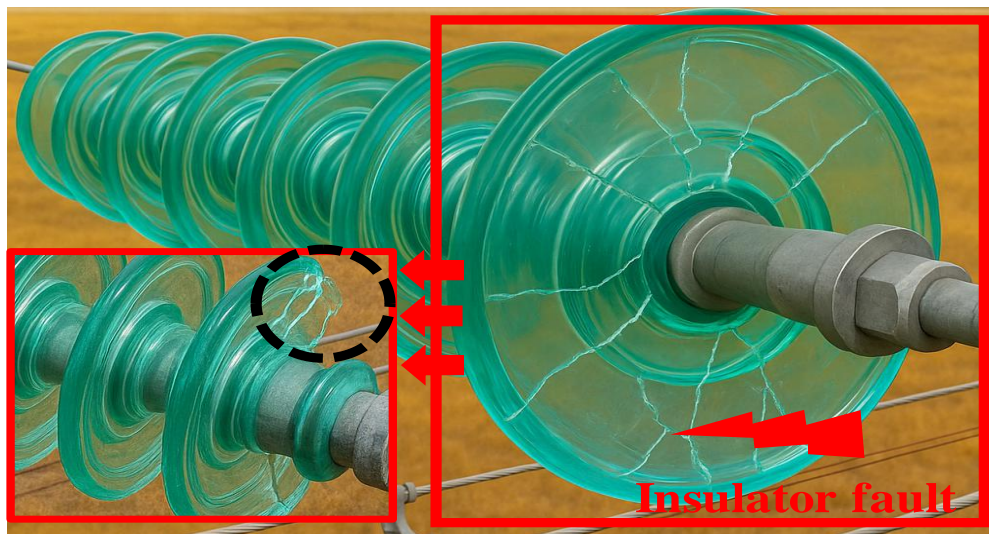


Figure II.1. Real insulator destroyed (damaged) in service.

II.3. Degradation of insulators under simultaneous mechanical damage and pollution stress

The presence of contaminants on the surface of an electrical insulatorsuch as dust, moisture, salts, or industrial fumes can lead to the formation of partially conductive paths along the surface, commonly known as surface conductive paths.

These paths significantly reduce the insulator's ability to withstand high voltage and increase the likelihood of partial discharges or even surface arcing.

On the other hand, when the insulator surface is damaged (through cracks, scratches, or fractures) caused by mechanical or thermal stress it loses part of its insulating capability. This damage disturbs the uniform distribution of the electric field across the surface, leading to field concentration in the weakened areas. However, the greatest risk arises when both factors occur simultaneously:

✚ **Damage** concentrates the electric field at specific points.

✚ **Pollution** creates a conductive environment on the surface.

As a result, the insulator becomes much more susceptible to sudden performance degradation, and surface arcing or complete electrical breakdown can occur at a voltage far lower than what a healthy insulator can normally withstand.[18,19]

II.4. Response of defective insulators to high voltage

When insulators are physically damaged whether through cracks, surface wear, or mechanical stress their electrical behavior under high voltage deviates significantly from normal. These imperfections create a localized area where the electric field intensifies, which promotes the early development of leakage currents. As environmental factors like humidity and pollution increase, these currents grow stronger and can ultimately trigger partial discharge activity.[18]

II.5. Insulator modeling

The studied insulator is a tempered glass suspension insulator, as shown in Figure II.2, used in high-voltage overhead transmission lines. It consists of a chain of ten units mechanically assembled to provide sufficient electrical insulation for the operating voltage.

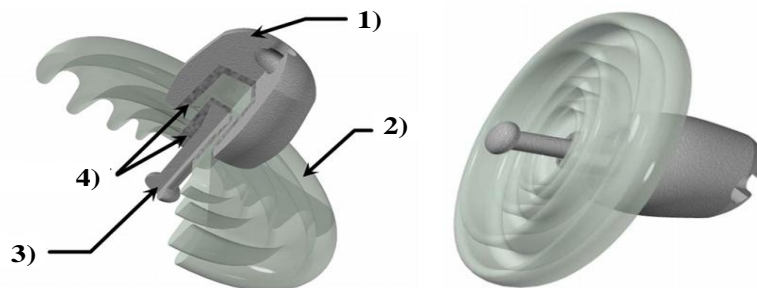


Figure II.2. Glass insulator assembly: 1) Cap, 2) Toughened Glass (Dielectric Body), 3) Pin, 4) Cement Mortar (Fixing Cement).

This type of insulator is specially designed to operate in outdoor environments exposed to various climatic and pollution constraints. Thanks to the combination of its components, it offers excellent dielectric strength, even in the presence of salt deposits, dust or atmospheric icing.[1]

Each unit in the chain comprises:

II.5.1. Insulating Part: Tempered glass

Tempered glass is selected for its excellent mechanical, electrical, and thermal shock resistance properties.

It must be homogeneous, free of air bubbles larger than 5 mm in diameter, and without surface defects such as folds or blisters, in order to ensure proper performance during service(Figure II.1).[20]

II.5.2. Metal cap

The cap, designed to house a ball-and-socket joint, is made of ferritic malleable cast iron or nodular cast iron. It is hot-dip galvanized to enhance corrosion resistance.

✚ Tensile strength: between 340 and 700 N/mm²,

✚ Elongation: > 10%,

✚ Zinc coating: average of 600 g/m² (85 μm), minimum of 500 g/m² (70 μm). In polluted areas, the coating can reach 790 g/m² (110 μm).[17,20]

II.5.3. Locking pin

The pin, typically made of stainless steel or phosphor bronze, ensures the mechanical safety of the assembly by preventing unintentional disengagement of the ball joint during handling or operation. Its dimensions are standardized.[17,20]

✚ Rod

The rod, made of forged or cast steel and also hot-dip galvanized, connects the insulating part to the supporting elements. It must meet strict mechanical strength requirements in accordance with assembly standards.[17,20]

✚ Sealing material

The seal between the insulating part and the metal fittings is achieved using fused alumina cement or Portland cement, both capable of withstanding repeated thermo-mechanical cycles.[17, 20]

✚ Anti-Corrosion washer (Polluted areas)

In highly polluted environments (level 3 and above), a washer made of pure zinc (99.7%) is cast directly onto the rod. The fusion interface between the washer and the rod must cover at least 80% of the total contact surface.[17, 20]

II.6. Overview of Comsol Multiphysics

COMSOL Multiphysics, illustrated in Figure II.3, is a simulation software platform that uses finite element analysis to model and solve Multiphysics problems, including interactions between electrical, mechanical, thermal, and fluid dynamics systems. It is widely used in engineering and scientific research for virtual testing, optimization, and analysis of complex systems.



Figure II.3. Presentation of the Comsol Multiphysics software.

One of its key strengths is its user-friendly interface, which features an intuitive graphical user interface (GUI) for setting up simulations.

This streamlined workflow allows users (from beginners to experts) to efficiently create, modify, and visualize models. Comsol offers specialized physics modules in its library, each dedicated to modeling specific physical phenomena.

These modules can be seamlessly coupled to build sophisticated Multiphysics models, enabling customized simulations for advanced research and engineering applications.[6]

II.7. Simulation workflow in Comsol Multiphysics

The simulation process in Comsol Multiphysics follows a structured workflow to ensure accuracy and efficiency.

The software employs the finite element method (FEM) to compute electric fields in electrostatic domains and magnetic fields in magneto-static domains, enabling precise analysis of complex geometries and field distributions.

One of the key advantages of Comsol Multiphysics is that it does not require in-depth mathematical or numerical analysis expertise.

The necessary equations are predefined, allowing users to focus on specifying the domain (e.g., electromagnetics, heat transfer, or acoustics) and the mode of operation (steady-state, time-dependent, etc.) when constructing their models.

Additionally, Comsol can interface with external programming environments such as MATLAB to enhance computational capabilities.

Below, figure II.4 presents a structured diagram outlining the four main steps of the simulation process in Comsol Multiphysics[6]:

Step 1: Geometry creation (Physical model)

- ✚ The geometry is designed in AutoCAD and imported into Comsol.
- ✚ An insulator element (or a chain of insulators) is defined using an interface.
- ✚ Inputs include the x and y coordinates of all points defining the insulator geometry.

Step 02: Physics setup

- ✚ Material properties (e.g., cap-and-pin, glass, porcelain, and air) are assigned, including permittivity and conductivity.
- ✚ Boundary conditions and applied voltages (e.g., high voltage (HV) and ground (0V)) are configured.

Step 03: Mesh generation

- ✚ A **user-controlled mesh** is automatically generated.
- ✚ Parameters such as **element size** and free quad settings are applied for optimal discretization.

Step 04: Solver configuration

A default solver sequence is defined for stationary analysis to compute the electric field and potential distribution.[1]

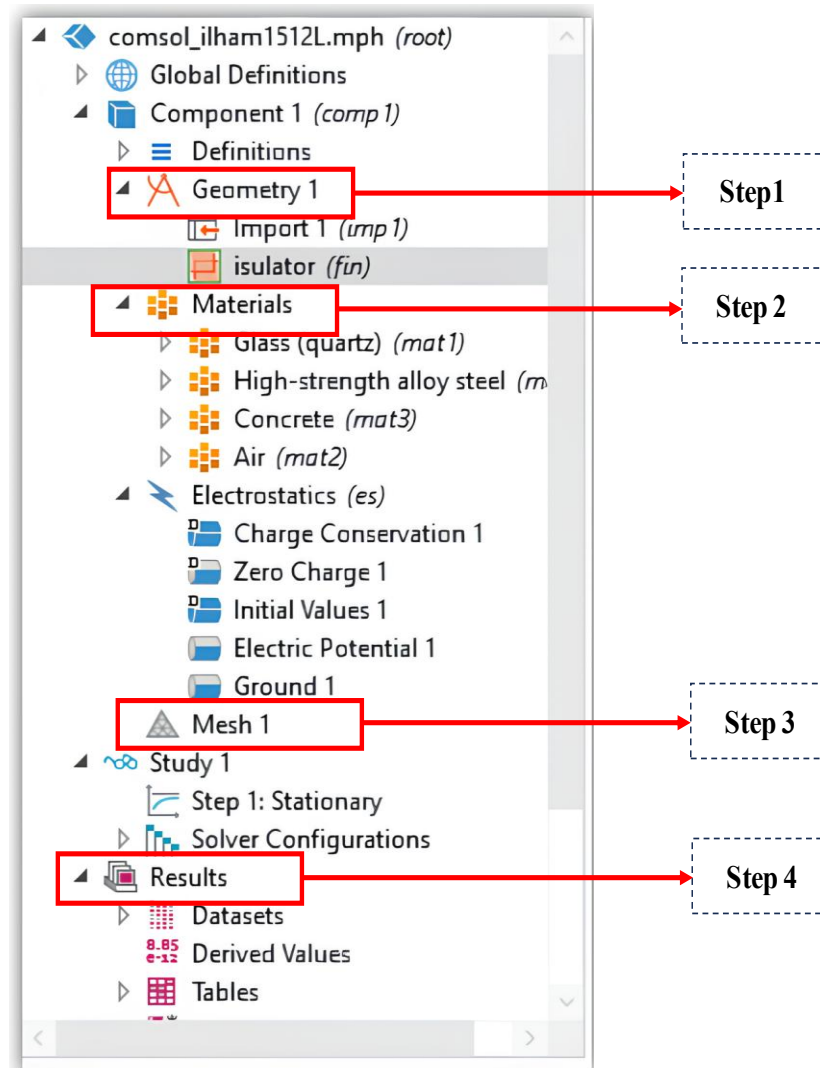


Figure II.4. The structure identifying the main steps for the Comsol model creation.

II.7.1. Calculation method

In Comsol Multiphysics, electrostatic problems are modeled using Maxwell's equations under the electrostatic approximation, which assumes the absence of time-varying magnetic fields. The governing equation is derived from Gauss's law for electricity and the definition of the electric potential.

To compute the electric field efficiently, Comsol utilizes the gradient of the electric potential (V), as the electric field (E) is related to the potential by:[21]

$$E = -\text{grad}V \quad (\text{II.1})$$

Obtaining Poisson's equation is exceedingly simple, for from the point form of Gauss's law:

$$\nabla D = \rho \quad (\text{II.2})$$

The definition of D

$$D = \varepsilon E \quad (\text{II.3})$$

and the gradient relation, (equation 1) or:

$$E = \nabla V \quad (\text{II.4})$$

By substitution equ.2, 3 and 4) we have:

$$\nabla \cdot D = \rho = \nabla \cdot (\varepsilon E) = -\nabla \cdot (\varepsilon \cdot \nabla V) = \rho \quad (\text{II.5})$$

or:

$$\varepsilon \nabla \cdot (\nabla V) = -\rho \quad (\text{II.6})$$

Laplace's equation takes the following shape when the space charges are ignored:

$$\varepsilon \nabla \cdot (\nabla V) = 0 \quad (\text{II.7})$$

II.7.2. Finite element analysis of insulators using Comsol Multiphysics

The study chosen for this model is the stationary study, which is a study that does not depend on any variable such as time or position or any such variable meaning that it does not change as the simulation progresses.

For the physics, it is the electrostatics physics. For this, we need to speak about certain things, which revolve around previous works and some thoughts that come to us. Previous researchers and engineers used conductivity as a main property to study flashover and leakage current and such terms for insulators but that is unnecessary for our physics and the only needed material property is the relative permittivity since we are studying the potential and field distribution.

Additionally, conductivity is a property that may define many materials or many conditions, which the pollution is in, whether it is moisturized or dry, and the same can be said for the relative permittivity. Each material has a relative permittivity that it is defined by and it can change depending on the state the pollution is in or if it is mixed with others.[6]

II.8. Insulator geometry

Comsol Multiphysics is powerful simulation software used for analyzing and visualizing electric field distributions, among other applications. Accurate geometry modeling is essential for reliable results, especially in complex three-dimensional (3D) cases. To facilitate this, Comsol supports interoperability with specialized CAD software such as AutoCAD, Solid Works, and Inventor.

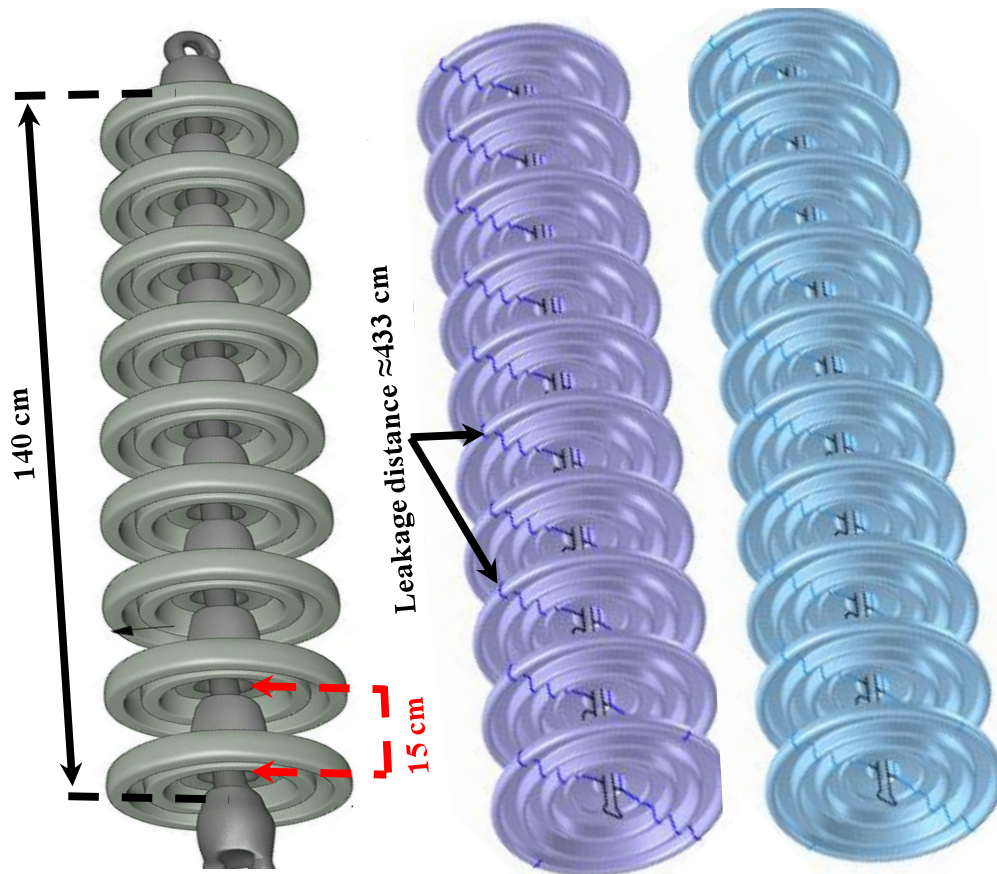


Figure II.5. General glass insulator dimensions AutoCAD and Comsol.

With the LiveLink™ for AutoCAD interface, users can seamlessly transfer 3D geometries from AutoCAD to Comsol Multiphysics. The synchronized geometry remains associative, meaning any modifications whether geometric, physical, or mesh-related are preserved during subsequent updates[1].

In this study, we analyze a suspension insulator assembly composed of ten (10) 1512L-type glass insulators, as shown in Figure II.5 above.

Each insulator unit has a pitch of **14.50 cm**, a diameter of **15 cm**, and contributes to a total leakage distance of approximately ≈ 433 cm for the entire chain.

II.9. Domain identification in Comsol Multiphysics software

Four domains are analyzed in this work (see Table II.1 and Figure II.6), with each domain defined by its relative dielectric constant and conductivity. These parameters were sourced from either the materials library or published references. The key properties of the selected insulator are provided in the table below:

Table II.1. The model material properties.

Material	Relative permittivity
Iron	10^6
Glass	4.2
Cement	5.9
Air	1.0006

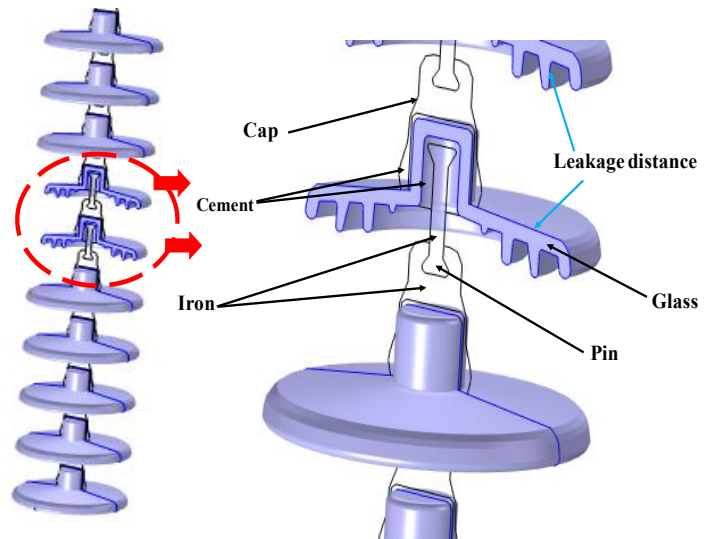


Figure II.6. Identifying the different areas domains of the glass insulator.

II.10. Mesh Analysis, potential, and electric field distribution

This section details the meshing methodology employed for the insulator chain and evaluates the resulting electric potential and electric field distribution. A structured mesh was generated with special emphasis on element density refinement in critical regions particularly near insulator edges and electrodes to ensure high numerical accuracy in the simulation.

II.10.1. Domain meshing

The quality of the mesh directly determines the reliability of simulation outcomes [1]. For our three-dimensional analysis, we employed a hybrid discretization approach incorporating tetrahedral, pentahedral, and hexahedral elements. Particular attention was given to mesh refinement in critical regions, specifically around insulator interfaces and metal components, to ensure solution accuracy.

The final mesh configuration represents an optimal compromise between computational efficiency and result fidelity, as visually documented in Figure II.7.

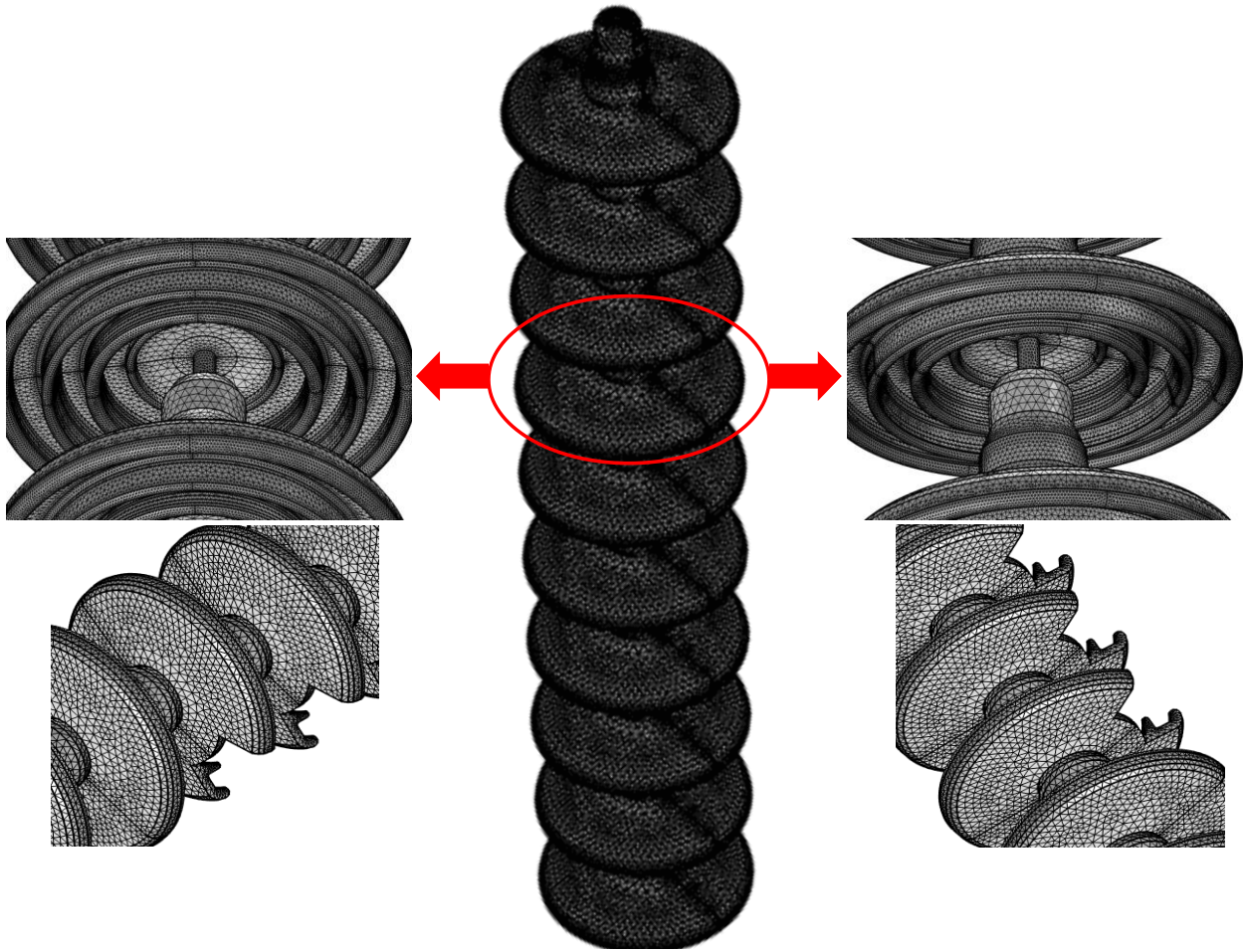


Figure II.7. Mesh for glass insulators.

II.10.2. Distribution of the potential

Figure II.8 presents the electric potential distribution across the insulator chain under applied high voltage. The results demonstrate a uniform voltage gradient along the length of the insulator, indicating consistent dielectric properties and proper surface conductivity.

Notably, the region near the high-voltage (HV) electrode exhibits the highest electric field intensity due to strong electrostatic stress concentration, which is characteristic of such asymmetric electrode configurations.

Conversely, the potential gradually decreases along the insulator surface, reaching near-zero values in the vicinity of the grounded (earth) electrode.

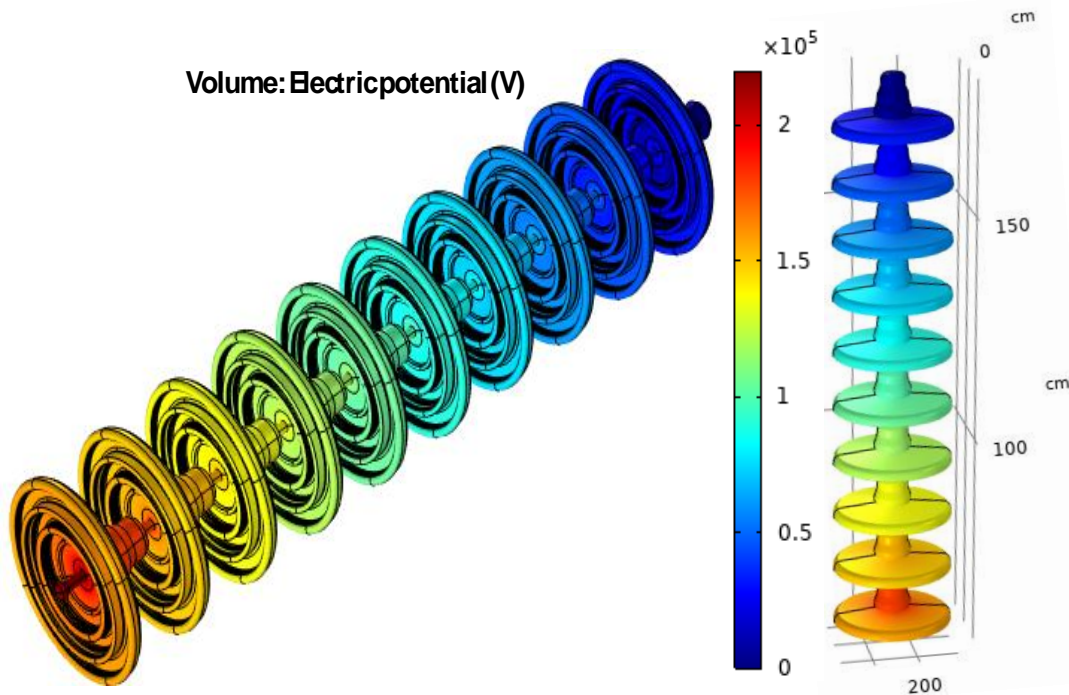


Figure II.8. Distribution of the potential in a glass insulator chain.

II.10.3. Distribution of the field

The electric field is a vector quantity that represents the force experienced by a unit positive charge placed in space. In practical applications, such as high-voltage systems, the electric field's behavior determines how charges interact with insulating materials, conductors, and surrounding structures. Visualization tools like field lines illustrate its spatial distribution, with density indicating field strength and tangents showing direction.

In high-voltage engineering, analyzing the spatial distribution of the electric field is critical for designing, optimizing, and safeguarding insulation systems. High-voltage equipment (e.g., transformers, cables, switchgear) operates under extreme electric potentials, where uneven field distributions can induce electrical stresses exceeding material limits. Engineers use computational tools like Finite Element Analysis (FEA) or experimental methods (e.g., electrostatic probes) to map field gradients. A well-distributed field ensures:

- ✚ Uniform stress across insulation, preventing premature aging.
- ✚ Corona suppression, reducing energy loss and electromagnetic interference.
- ✚ Deviations from ideal distributions often signal design flaws (e.g., sharp edges, air gaps) requiring mitigation via grading rings, optimized geometries, or composite insulation.

Non-uniform field distribution can lead to local overstressing, partial discharges, and eventually insulation failure.[22]

Figure II.9 shows the electric field distribution along the insulator under high voltage. The highest field intensity appears near the HV electrode due to strong electrostatic stress, while the field gradually decreases toward the grounded side. This indicates effective voltage sharing and highlights areas of potential dielectric stress.

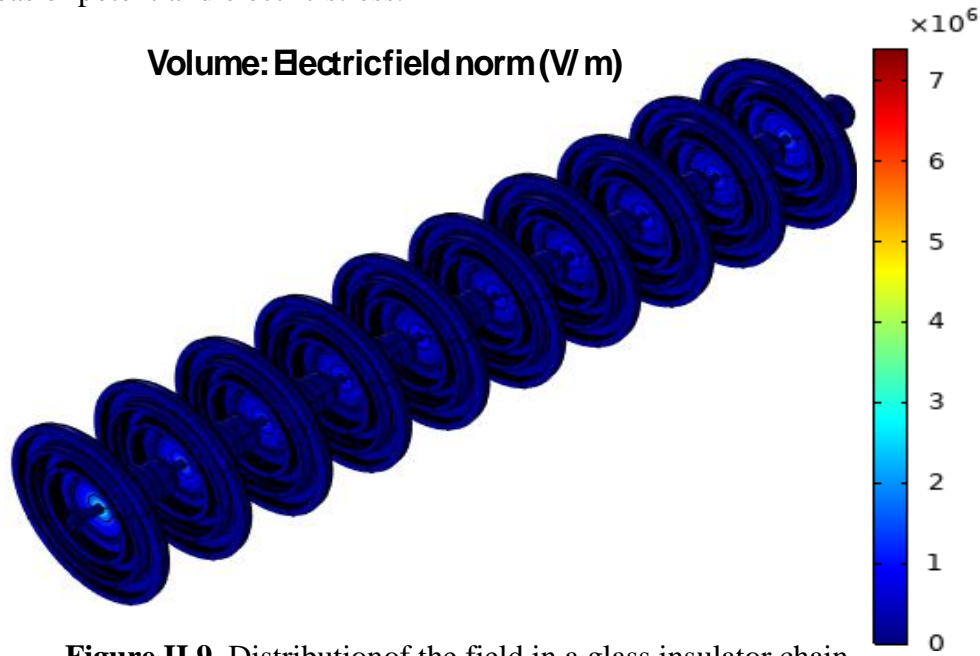


Figure II.9. Distribution of the field in a glass insulator chain.

II.11. Conclusion

This chapter employed COMSOL Multiphysics to investigate the effects of mechanical damage on high-voltage insulators using 3D finite element simulations. The study focused on the modeling of intact insulators, analyzing their geometry, mesh configuration, and electric field distribution under controlled conditions. The simulation workflow in Comsol Multiphysics was explored to understand the interplay of electrical, mechanical, and environmental stresses on insulator performance. This groundwork provides a robust foundation for evaluating insulator behavior and highlights the critical role of advanced simulation tools in optimizing design and preventing failure in high-voltage applications.

The next chapter will present a detailed 3D simulation analysis of the insulator chain under various damage scenarios offering deeper insights into their performance under complex and degraded conditions.

Chapter III

**"Analysis and Results of Performance Degradation in
Damaged Insulators"**

III.1. Introduction

The voltage distribution around an insulator is obviously linked to the insulator geometry and the electrical properties of the constituent materials. Two-dimensional voltage and electric field calculations are valid for symmetrical geometries, but if the geometry is asymmetrical, 2D analysis is not sufficient. A 3D model is required for greater accuracy.[1]

In this chapter, the results of a 3D simulation performed using COMSOL Multiphysics will be presented and analyzed. The main objective of this simulation of the insulators is to study the effect of mechanical damage at different locations of the insulator on the electric field distribution, and to observe changes that may lead to the formation of leakage currents or partial discharges. In addition to evaluating the effect of damage at different locations of the insulator, in order to understand the changes in electrical performance, such as the appearance of leakage currents or partial discharges. A comparison was made between clean and damaged states of the insulator under the same operating conditions, in order to determine the extent to which its dielectric efficiency has deteriorated.

This numerical evaluation helps to support preventive maintenance strategies and minimize the likelihood of sudden failures in power transmission networks.

III.2. 3D simulation

In this study, a three-dimensional (3D) simulation using COMSOL Multiphysics was employed to analyze the electric field distribution in high-voltage insulators. 3D modeling is particularly essential when dealing with asymmetric geometries or internal defects, as it provides a more realistic and accurate representation of electric field behavior under complex environmental conditions. Compared to 2D simulations, 3D models can capture spatial variations and localized effects.[23]

A three-dimensional model of a **1512L type glass insulator** under high-voltage conditions, simulating real-world operation, was developed. Three damage scenarios were then analyzed:

- ✚ **First scenario:** A fracture or crack at the base (lower end) of the insulator.
- ✚ **Second scenario:** Damage in the middle section of the insulator.
- ✚ **Third scenario:** A fracture at the top (upper end) of the insulator.

Figure III.1 illustrates the three studied cases corresponding to these damage stages.

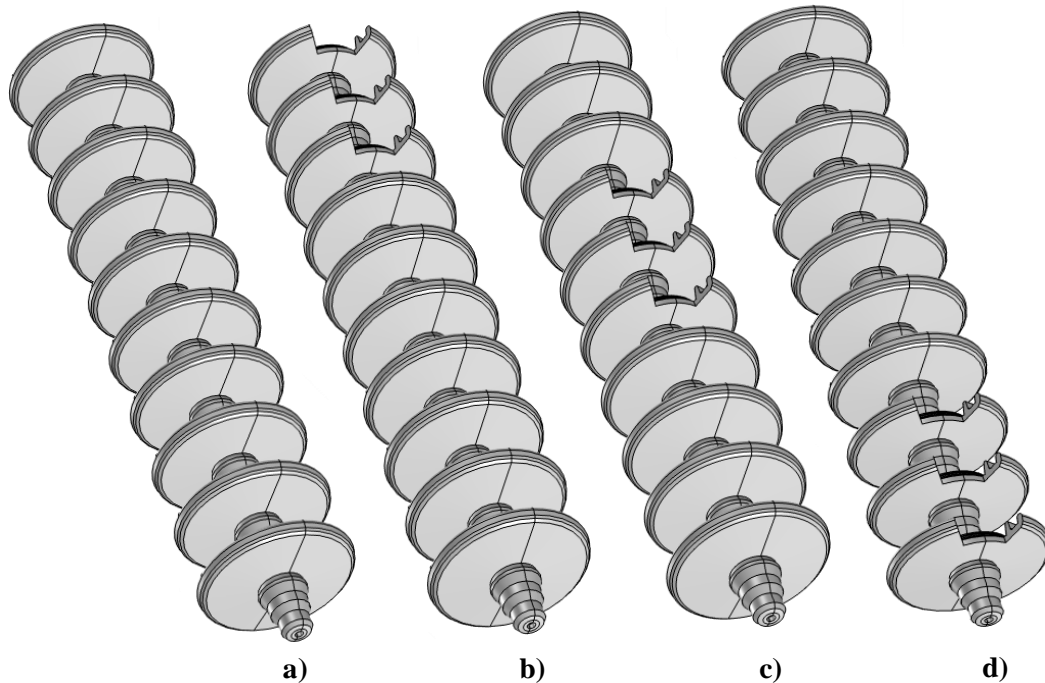


Figure III.1. Geometric model for incomplete glass insulators, a) No damage, b) Low damage, c) Middle damage, d) Upper damage.

At every scenario, the distribution of the electric field was examined, and the areas of voltage concentration along with the distortions in the field lines were mapped.

III.3. Simulation conditions

The boundary condition for our model is two; the first one is the electric potential boundary, which is the pin of the first insulator in the chain with a voltage of 220 kV. The second boundary is the ground boundary, which is the cap of the last insulator.

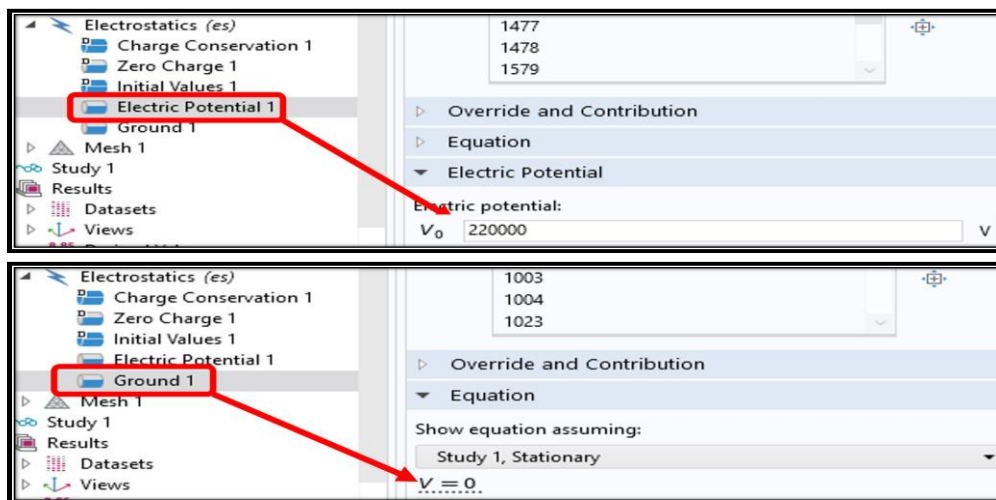


Figure III.2. The boundary condition of the electric potential, ground.

III.4. Meshing effect

The software's default mesh, which is typically suitable for thin and intricate issues that may arise due to small geometry shapes, is used to create the majority of generated meshes in general.

However, the software also offers other meshing choices, such as a mapped mesh or a free quad mesh and demonstration of mesh features includes: 1) an unstructured triangle mesh, 2) a structured quad mesh, 3) a higher-order mesh, 4) an isotropic mesh, 5) an anisotropic graded mesh, and 6) a linear mesh. All having the same number of elements, but differing in shape accuracy. These meshing options are chosen based on the geometry characteristics.[24]

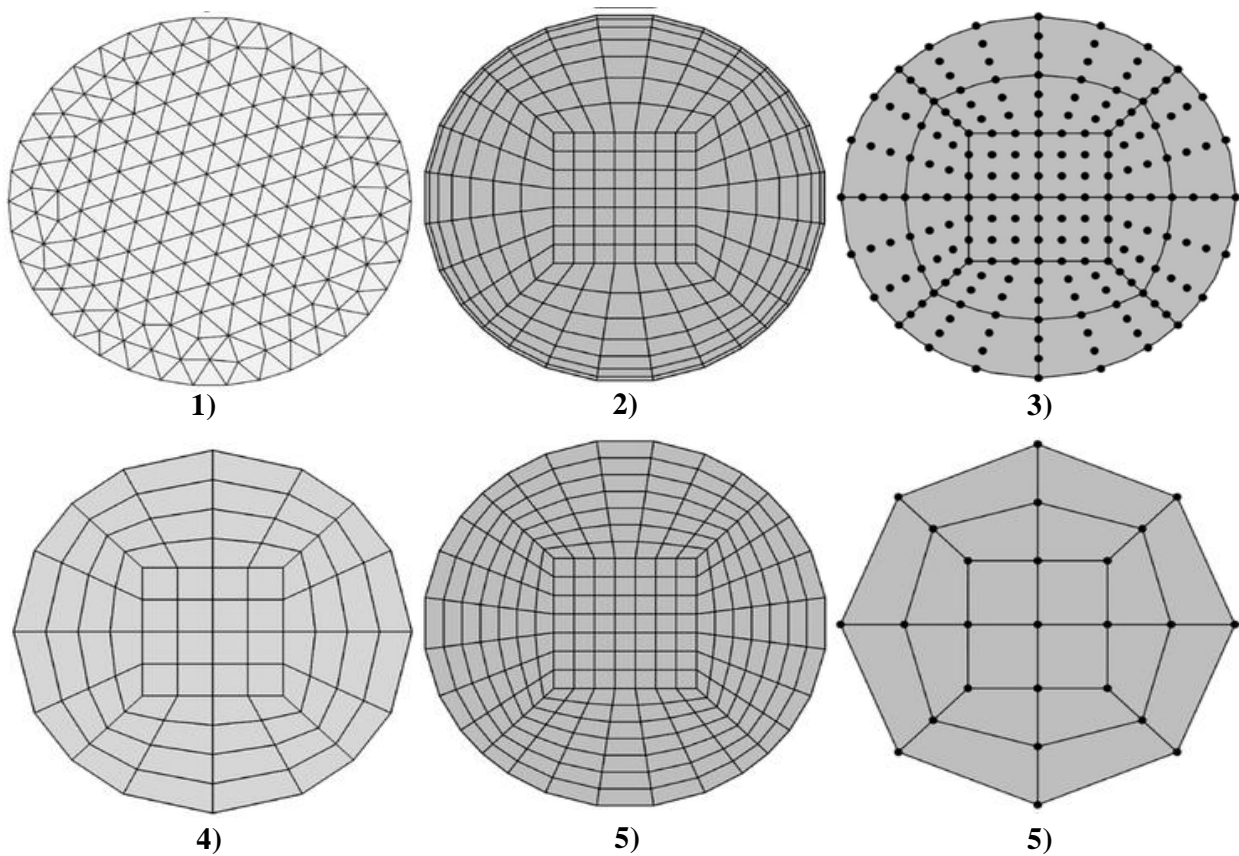


Figure III.3. Mesh Topologies (Mesh Configurations, Types of Meshes).

In figure III.4, the default meshing option, free triangular mesh, was used to create our mesh. This mesh is suitable for the small geometries that surround the small edges of the geometry, which are depicted in the figures below as black spots but are actually small triangular shapes. The mesh always has a triangular form despite being smaller in size near the edges and in tiny areas of the insulator.[6]

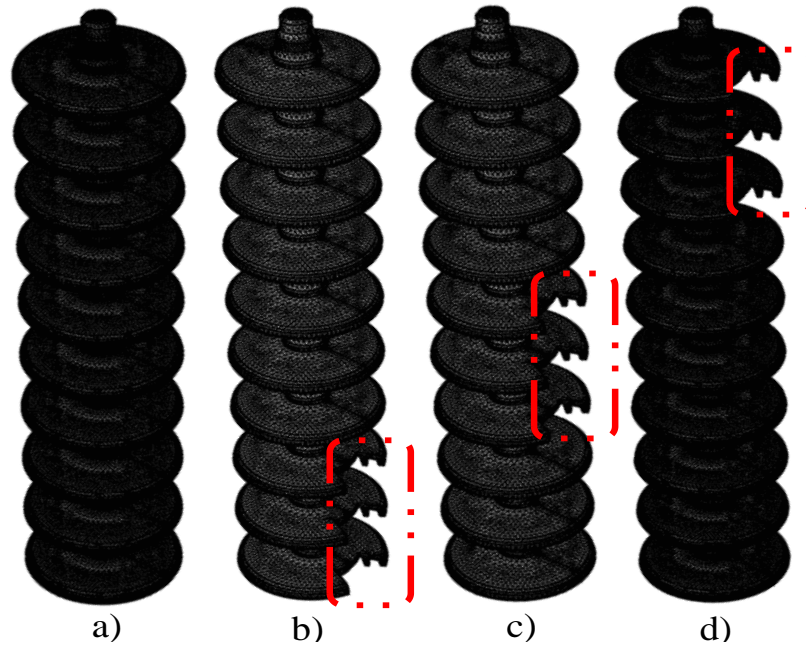


Figure III.4. Meshing effect, a) No damage, b) Low damage, c) Middle damage, d) Upper damage.

III.5. Results and discussion (Analysis of results)

This section is dedicated to the study of the voltage and electric field distributions of the insulator along the leakage distance. The potential distribution is calculated along the total leakage path (indicated by the blue reference line), as shown in the figure III.5.

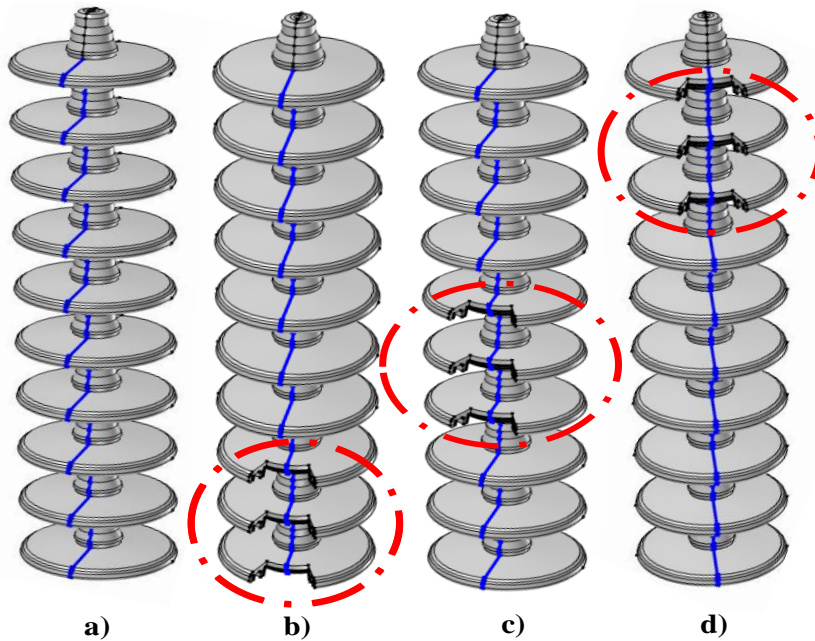


Figure III.5. The reference lines for glass insulators. a) No damage, b) Low damage, c) Middle damage, d) Upper damage.

Figure III.6 illustrates how the leakage distance is determined. In Figure III.6 (a), the leakage path is measured along the surface of a clean insulator, following the standard leakage path. In contrast, Figure III.6 (b) shows the leakage distance for a damaged insulator, where the fracture introduces irregularities that may shorten or distort the leakage path, thereby affecting the insulation performance.

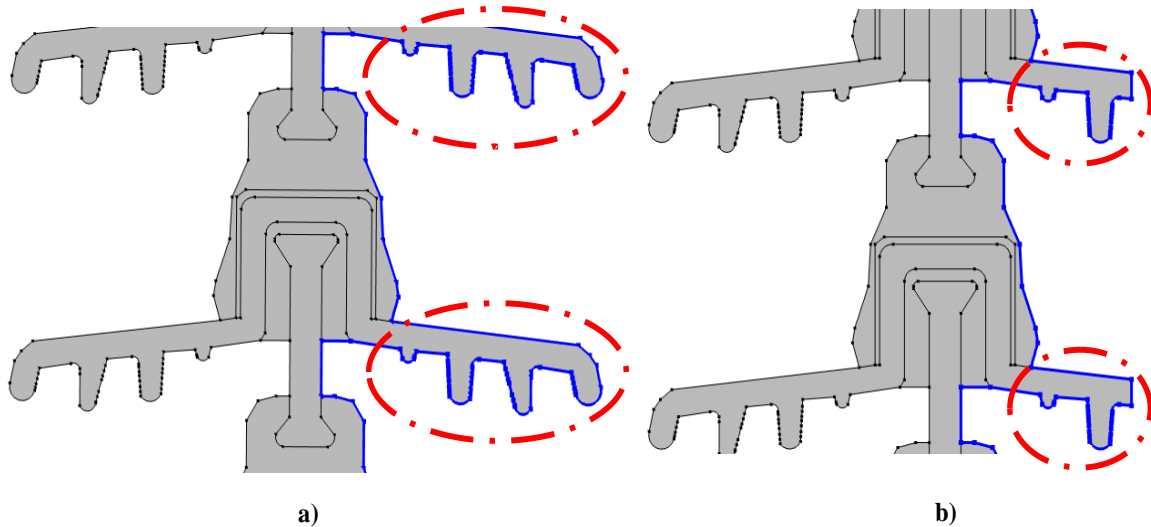


Figure III.6. Illustration of the leakage distance. (a) Clean insulator showing the leakage distance along the surface, (b) Fractured insulator with a modified leakage path due to the break.

III.5.1. Electric potential distribution

The performance of high-voltage insulators under mechanical and structural degradation is a critical factor influencing the reliability, design, and insulation quality of power systems. Mechanical defects, such as cracks or damage, can distort the electric field distribution and create localized regions of high electric stress, significantly increasing the risk of dielectric breakdown. Understanding these mechanisms is essential for monitor the effectiveness of a structure's insulation.[25]

The pictures below show a 3D volume plot, depicting the distribution of electrical potential across the surfaces of the insulators examined.

In the area between the electrode and earth, the voltage distribution is uniform. It can also be seen that the maximum potential values are close to the high-voltage electrode and start to decrease until they are cancelled out when approaching the ground electrode.[1]

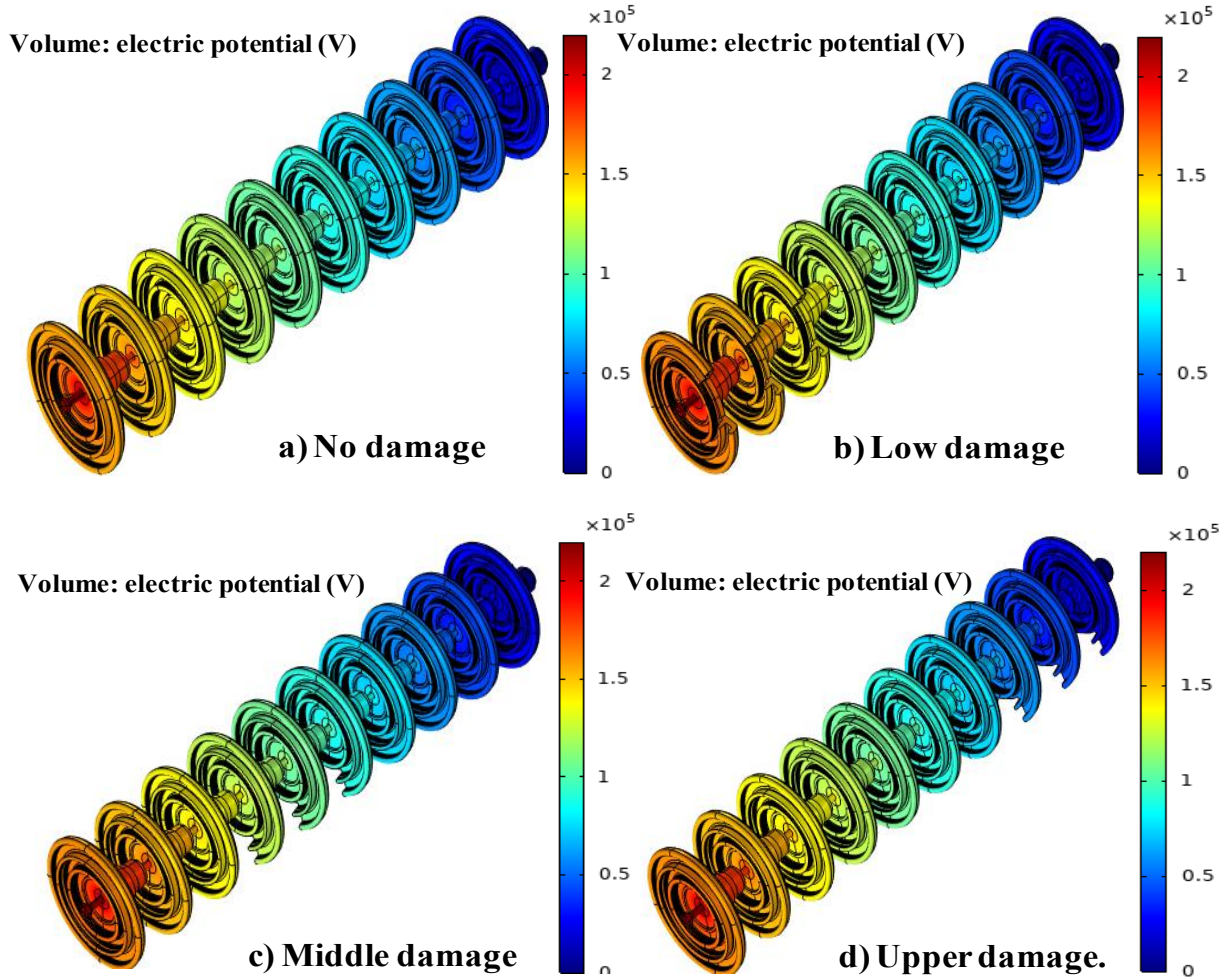


Figure III.7.Electrical potential distribution of glass insulators.

In the following we will convert the results obtained by COMSOL Multiphysics into curves.

These curves represent the variation of the electric potential along the total leakage path for both damaged insulators and a healthy one for comparison purposes. The 1D plot in Figure III.8 provides a more detailed understanding of how the values change along the leakage distance, while the volume plot offers a clearer visualization of the electric potential.

Four cases were studied:

- ✚ Undamaged (clean) insulator –indicated in blue.
- ✚ Insulator with damage at the base (lower end) – indicated in red.
- ✚ Insulator with damage in the middle section – indicated in black.
- ✚ Insulator with damage at the top (upper end) – indicated in green.

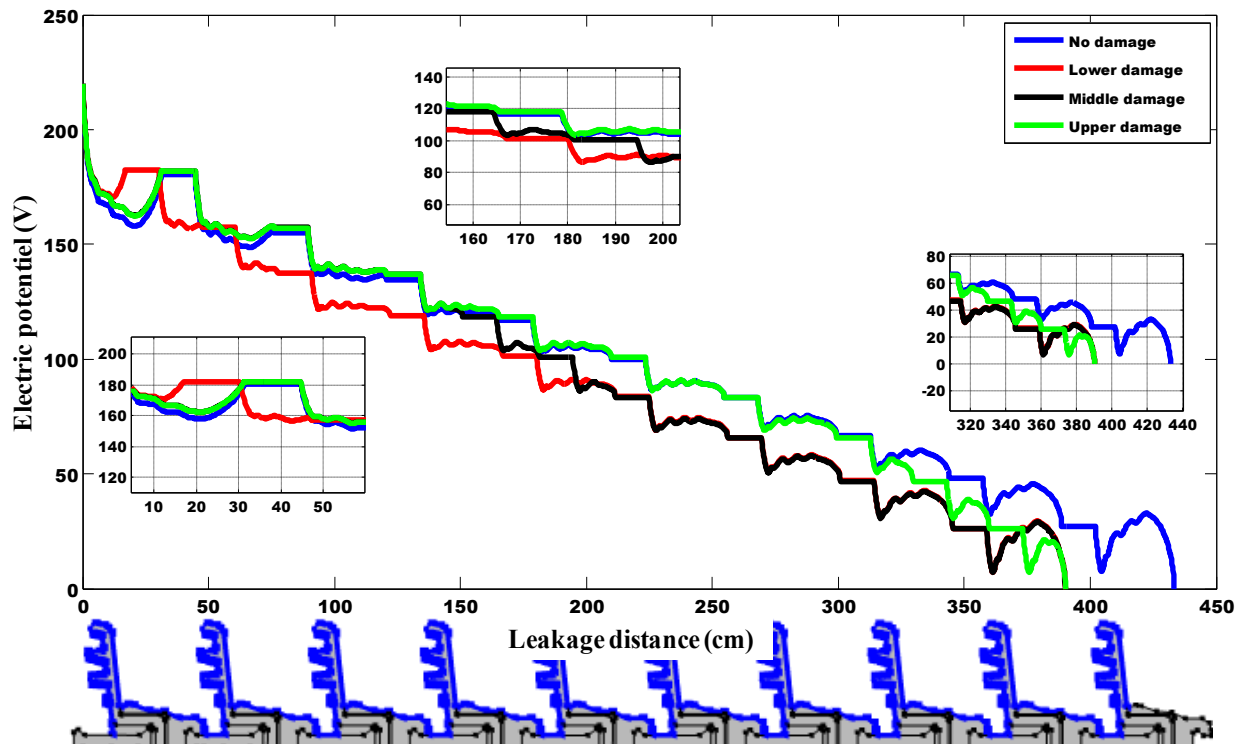


Figure III.8. Radial electric potential distribution: Undamaged vs. damaged cases.

The most noticeable observation is that the intact insulator displays a smooth and continuous potential gradient along the leakage path, indicating stable insulation performance.

In contrast, the damaged insulators show clear disruptions in the potential distribution. When the damage is located at the start, the potential drops sharply near the beginning of the leakage path, suggesting an early disturbance in the field distribution.

For the middle damage, irregularities appear in the central region, where the electric stress is more concentrated and uneven.

In the case of damage at the end, the potential shifts significantly near the grounded end, indicating higher electric field intensity in that area.

While the overall trend of potential decrease is preserved, the location of the damage clearly affects the field distribution and can lead to increased risk of surface discharge or flashover.

This underlines the importance of 3D simulation in assessing the impact of structural damage on the electric performance of insulators.

III.5.2. Electric field distribution

Figure III.9 illustrates the electric field distribution, representing the spatial variation of electric force per unit charge within the analyzed region.

In high-voltage systems, analyzing this distribution is crucial for evaluating insulation performance, as field non-uniformities may cause partial discharges or dielectric breakdown. Key influencing factors include system geometry, material dielectric properties, and applied voltage characteristics.

Numerical simulations enable detailed visualization of field patterns, especially near structural defects or geometric discontinuities where field intensification typically occurs. Proper understanding and management of electric field behavior are fundamental to insulation system design and operational reliability.

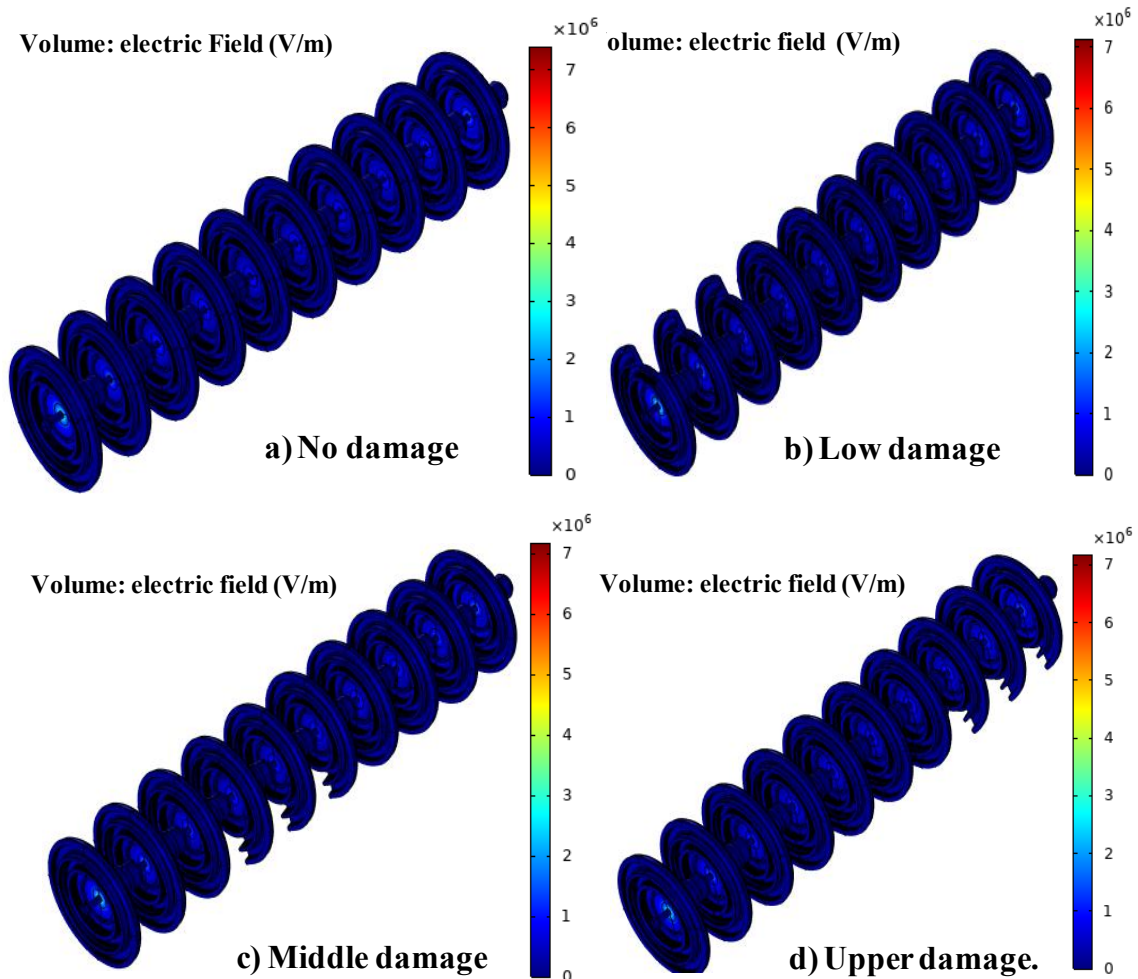


Figure III.9. Electric field distribution of glass insulators.

The analysis shows the strongest electric field variations occur at the pin-cap interface of each insulator. To evaluate differences between damaged conditions and the undamaged insulator chain, as well as between different failure scenarios, we generated comparative 1D field plots. The subsequent diagrams display the electric field distribution along the insulator string relative to leakage distance.

The plot in Figure III.10 reveals that the electric field intensity increases significantly in the damaged cases, with the location of the damage influencing the pattern and severity of the distortion.

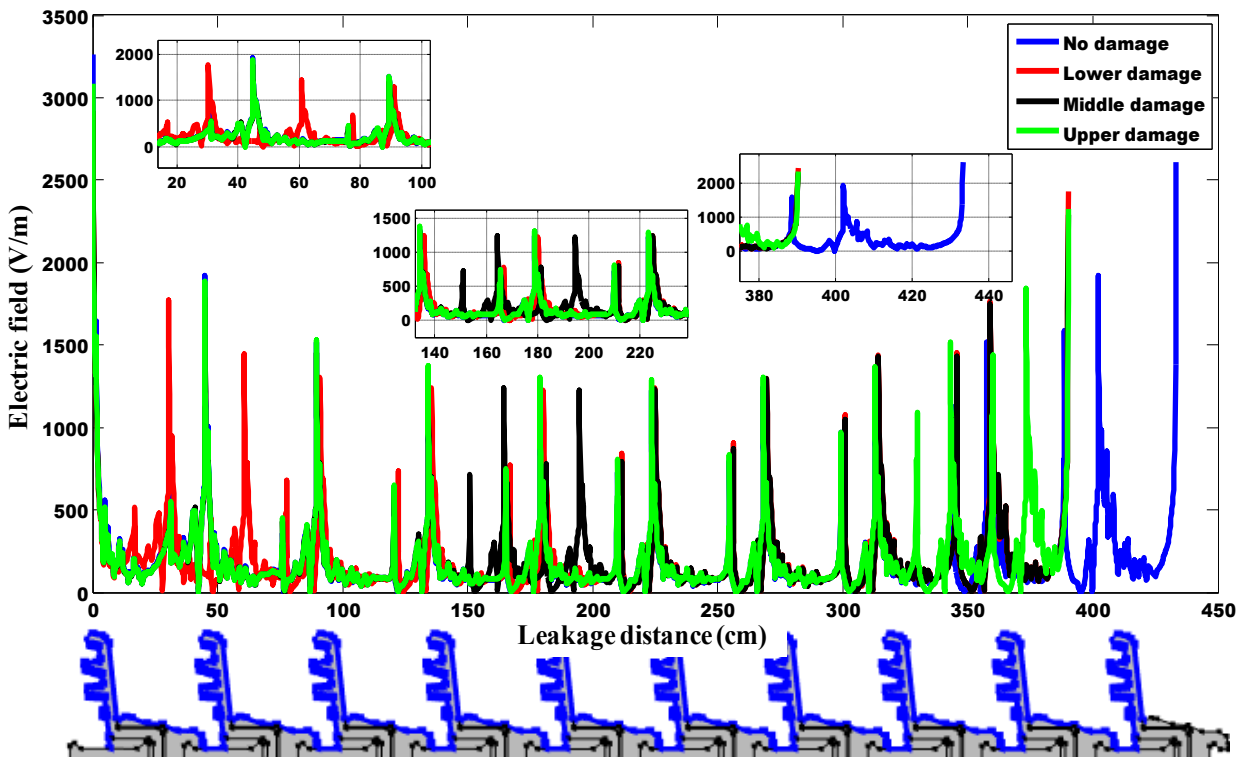


Figure III.10. Radial electric field distribution: Undamaged vs. damaged cases.

When the damage is located at the start, the field exhibits a sharp spike at the beginning of the leakage path, indicating a concentrated stress point due to the early interruption of insulation continuity. For the middle damage, the field is disturbed more prominently in the central region, suggesting potential areas of partial discharge or surface tracking. In the case of end damage, the field intensity increases near the grounded end, raising the risk of flashover close to the electrode. The clean insulator, in contrast, maintains a more uniform field distribution along the leakage path.

This comparison highlights that damage location plays a critical role in determining electric stress behavior and emphasizes the importance of localized field analysis in assessing insulation reliability. The values for each study are summarized in the table below.

Table III.1. The values of the electric field and the electric potential.

Aspect	The electric potential	The electric field
Main Objective	It focused on the voltage along the leakage path, i.e., how the voltage gradually decreases from the high-voltage side (pin side) to the ground side, and how damage affects this voltage gradient.	Focus on electric field intensity, which is the spatial derivative of voltage, i.e., how steep the voltage is at a given point—the steeper the gradient, the higher the field intensity. High field intensity can indicate weak points where electrical discharge or insulation breakdown may occur.
Type of Potential Risk	Voltage imbalance may lead to uneven insulation distribution.	Risk of discharge or localized insulation breakdown.
Key Insight	Damage alters the voltage distribution curve, which helps locate changes in insulation behavior along the path.	Damage causes electric field concentration at specific locations, which clearly highlights critical points vulnerable to failure.

The distribution of the electric field is greatly influenced by the position of mechanical damage within the insulator. Among the three scenarios examined breakage at the start, middle, and end of the insulator the most significant distortion of the electric field was observed when the breakage occurred near the high-voltage end.

This arrangement led to the highest concentration of the electric field, indicating an increased risk of electrical discharge. In contrast to the electric potential, which displayed a relatively smooth variation, the electric field showed more abrupt changes in the vicinity of the damaged areas. These findings imply that the location of the break is more crucial than its mere existence, and the extent of the field distortion is heavily influenced by the break's proximity to high-voltage elements.

III.6. Conclusion

Our numerical models have produced insightful results regarding the performance of insulators under different damage conditions.

The three-dimensional simulation offered a more accurate representation of the real operating conditions. A 1512L glass insulator was modeled with damage scenarios at three different locations: Lower, middle, and upper. These simulations revealed that the position of damage significantly affects the field distribution. Notably, damage at the upper and middle leads to more pronounced electric field intensities compared to damage in the middle, emphasizing the importance of damage location in failure prediction. The voltage profile was also slightly disturbed, especially near the fracture zones, although the overall trend remained consistent.

COMSOL simulation results confirm that the location of damage on the insulator surface is a critical factor in determining the extent of electrical performance degradation. This numerical assessment supports the development of predictive models that help in making early maintenance decisions and minimizing the likelihood of sudden failures in high-tension networks.



"General conclusion"

General conclusion

In the thesis Analysis of Insulator Strings under Degraded Conditions: New Perspectives for Performance Assessment, we have thoroughly explored the effects of mechanical damage on high-voltage glass cap-and-pin insulators, focusing on its significant impact on the reliability of electrical energy transmission systems compared to pollution. The study shows that damage, such as cracks or structural issues, creates a more immediate and serious problem than pollution, often causing sudden flashovers, power outages, or lasting harm to network components.

In the first chapter, a clear overview of high-voltage insulators was given, explaining their key role in providing electrical insulation and mechanical support in power transmission systems. The review of previous studies and discussion of insulator types and challenges showed that mechanical damage, unlike the gradual effects of pollution, can lead to major failures, making it a top concern for system reliability.

In the second chapter, we entered the field of computer simulations, creating a simulated testing environment to investigate insulator behavior using COMSOL Multiphysics. The focus was on three-dimensional scenarios, particularly the electrostatic components, to understand how insulators perform under various conditions.

In the third chapter, the study examined insulator behavior under three damage scenarios: at the top, bottom, and alternating damage along the insulator. Additionally, the study analyzed voltage distribution across three types of insulators under clean, polluted, and damaged conditions, with different voltage forms applied.

The 3D simulations, supported by insulator models designed in AutoCAD, showed notable changes in electric field and potential distributions due to localized damage. These changes were much stronger than those caused by pollution, leading to sharp increases in the electric field that raise the risk of flashover and insulator failure.

The simulations also revealed that voltage and electric field distribution along a clean insulator are uniform due to the absence of a conductive pollution layer, while in humid conditions, the voltage distribution becomes uneven, influenced by the insulator's geometry.

These findings emphasize the need to focus on mechanical strength in insulator design and maintenance to avoid sudden failures.

In summary, this study confirms that mechanical damage is a more serious threat to insulator performance than pollution, with significant effects on the reliability of high-voltage transmission lines. The FEM-based simulations, using COMSOL Multiphysics and AutoCAD for modeling, provided useful insights into the failure mechanisms of damaged insulators, offering a solid method for predicting and reducing risks.

For future research, it is suggested to validate these simulation results with experiments, study additional environmental and mechanical factors, and include other insulator types used in real-world applications. Additionally, developing improved insulator designs that address structural weaknesses and adopting predictive maintenance strategies will improve the durability and reliability of power transmission systems, ensuring a stable and efficient energy supply. Furthermore, future studies should investigate the combined effects of pollution and mechanical damage, as this combination poses an even greater risk than mechanical damage alone.



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