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Yüksek Gerilimli Ekipmanlarda Katı Yalıtım Sistemleri: Malzemeler, Yaşlanma Mekanizmaları, Tanılama Yöntemleri ve Gelecek Perspektifleri

Solid Insulation Systems in High-Voltage Equipment: Materials, Aging Mechanisms, Diagnostics, and Future Perspectives

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Özet

Katı yalıtım sistemleri, yüksek gerilimli (YG) elektrik ekipmanlarının güvenilirliğini, güvenliğini ve hizmet ömrünü sağlamada kritik bir rol oynamaktadır. Yağ–kâğıt yalıtımının ilk dönemlerdeki baskın kullanımından polimerik, reçine esaslı ve kompozit malzemelerin yaygın olarak benimsenmesine kadar, katı yalıtımın evrimi; dielektrik fiziğindeki gelişmeler, üretim teknolojilerindeki ilerlemeler ve artan işletme gereksinimleri tarafından yönlendirilmiştir. Son yıllarda YGDC iletim, ultra-yüksek gerilim işletimi, kompakt ekipman tasarımları ve sürdürülebilirlik gereksinimleri gibi ortaya çıkan zorluklar, katı yalıtım malzemelerinin ve performans sınırlamalarının yeniden ele alınmasına olan ilgiyi artırmıştır.

Bu derleme, YG ekipmanlarında kullanılan katı yalıtım sistemlerinin tarihsel gelişimini, güncel ileri teknoloji malzemelerini ve gelecekteki eğilimleri kapsayan kapsamlı bir analiz sunmaktadır. Selüloz esaslı sistemler, epoksi reçineler, polimerik ve termoplastik malzemeler, nanokompozitler ve inorganik yalıtkanlar dâhil olmak üzere başlıca katı yalıtım sınıfları; dielektrik, termal ve mekanik özellikleri açısından eleştirel olarak incelenmiştir. Termal bozunma, kısmi deşarj etkinliği, uzay yükü birikimi ve çevresel etkiler gibi temel yaşlanma mekanizmaları tartışılmıştır. Ayrıca, sürdürülebilir ve geri dönüştürülebilir yalıtım malzemeleri ve sistemleri gibi gelişmekte olan araştırma yönelimleri vurgulanmıştır. Mevcut sınırlamaların ve açık araştırma sorunlarının belirlenmesiyle, bu çalışma yeni nesil YG ekipmanları için katı yalıtım sistemlerinin gelecekteki gelişimine yönelik yapılandırılmış bir bakış açısı sunmaktadır.Anahtar

Kelimeler: Yüksek gerilim yalıtımı, Katı dielektrik malzemeler, Polimer yalıtım, Nanokompozitler, Yaşlanma mekanizmaları.

Abstract

Solid insulation systems play a critical role in ensuring the reliability, safety, and lifetime of high-voltage (HV) electrical equipment. From the early dominance of oil–paper insulation to the widespread adoption of polymeric, resin-based, and composite materials, the evolution of solid insulation has been driven by advances in dielectric physics, manufacturing technologies, and increasing operational demands. In recent decades, emerging challenges such as HVDC transmission, ultra-high-voltage operation, compact equipment design, and sustainability requirements have renewed interest in revisiting solid insulation materials and their performance limitations. This review presents a comprehensive analysis of solid insulation systems used in HV equipment, covering historical development, current state-of-the-art materials, and future trends. Major classes of solid insulation, including cellulose-based systems, epoxy resins, polymeric and thermoplastic materials, nanocomposites, and inorganic insulators, are critically examined in terms of their dielectric, thermal, and mechanical properties. Key aging mechanisms, such as thermal degradation, partial discharge activity, space charge accumulation, and environmental effects, are discussed. Furthermore, the review highlights emerging research directions, including sustainable and recyclable insulation materials and systems. By identifying current limitations and open research challenges, this paper provides a structured perspective on the future development of solid insulation systems for next-generation HV equipment.

Keywords: High-voltage insulation, Solid dielectric materials, Polymer insulation, Nanocomposites, Aging mechanisms.

1. Introduction

Solid insulation systems constitute a fundamental part of high-voltage (HV) electrical devices, significantly influencing their operational reliability, protection, and service lifetime [1, 2]. In power apparatus such as transformers, electricity cables, bushings, rotating machines, and switchgear, stable insulating materials offer mechanical support, electric separation, and long-time period dielectric balance under excessive electric stresses. Failures related to insulation degradation continue to be one of the number one causes of unplanned outages and costly preservation in power systems, highlighting the vital role of solid insulation design in cutting-edge electric infrastructure [3, 4].

Historically, insulation systems in HV devices have relied heavily on fluid dielectrics, specifically mineral oil, in combination with stable materials such as cellulose paper and pressboard. While liquid insulation gives advantages along with powerful heat dissipation and self-recovery properties, it cannot function independently without strong insulation additives that ensure structural integrity and electric area management [5-7]. Moreover, fluid insulation structures are inherently restricted by means of problems which include leakage, flammability, humidity absorption, environmental issues, and aging-related contamination. These barriers have pushed the modern integration and, in a few packages, partial replacement of conventional oil–paper systems with polymeric, resin-based, and composite solid insulation substances [4, 8, 9].

In recent decades, the running conditions of HV systems have become increasingly more stressful because of the rapid evolution of power transmission and distribution technology [10]. The expansion of high-voltage direct current (HVDC) transmission, the deployment of ultra-high-voltage (UHV) structures, and the trend toward compact and excessive-power-density gadgets have added new electrical, thermal, and mechanical stresses on insulation systems [11-13]. Under DC and combined AC/DC fields, phenomena inclusive of space charge accumulation and field distortion pose big demanding situations to traditional insulation substances. At the same time, sustainability requirements, environmental guidelines, and the need for recyclable and green substances are reshaping insulation fabric choice and system layout [14-16].

These emerging challenges necessitate a comprehensive reassessment of solid insulation structures, encompassing not only best fabric development but also aging and degradation mechanisms [17, 18]. Advances in material technology, mainly in polymer nanocomposites, thermoplastics, and functionally graded dielectrics, have opened new pathways for tailoring insulation properties.

The objective of this review is to provide a structured and critical overview of solid insulation systems used in high-voltage equipment, spanning historical developments, current state-of-the-art materials, and future perspectives. The review systematically examines major classes of solid insulation materials, discusses dominant aging and degradation mechanisms. Furthermore, emerging research directions such as sustainable insulation materials and computational insulation design are highlighted. By identifying current limitations and open research challenges, this paper aims to serve as a reference framework for researchers and engineers engaged in the development and application of next-generation solid insulation systems for HV equipment.

2. Evolution of Solid Insulation in High-Voltage Equipment

The development of solid insulation systems in high-voltage (HV) equipment has closely followed advances in electrical engineering, materials science, and power system requirements. From empirically designed oil–paper systems to sophisticated polymeric and composite dielectrics, each historical phase reflects both technological progress and emerging operational challenges. Understanding this evolution is essential for contextualizing current insulation technologies and identifying future research directions [19].

2.1. Early Insulation Systems (1900s–1950s)

During the early decades of electrical power engineering, solid insulation structures had been predominantly based on cellulose-derived materials, consisting of paper, pressboard, and wood, utilized in combination with mineral oil [20]. Oil–paper insulation rapidly became the same old solution for transformers, bushings, and early high-voltage apparatus because of its favorable dielectric strength, effective heat dissipation, and self-healing capability following electric discharges. In those systems, stable insulation provided mechanical support and controlled electric powered discipline distribution, while the liquid dielectric filled voids and provided better standard insulation performance [4, 21].

Design practices in this era have been largely empirical, counting on conservative protection margins derived from operational experience rather than fundamental information on dielectric phenomena [22]. Electric field distributions, aging behavior, and breakdown mechanisms have been poorly understood, leading to oversized insulation structures and restrained optimization. Nevertheless, oil–paper structures verified remarkable long-term reliability, with many early transformers working effectively for many years. Aging was mostly attributed to thermal strain and moisture ingress, even though degradation mechanisms such as partial discharge (PD) activity had not yet systematically recognized or monitored [23, 24].

Despite their success, early insulation systems were constrained by material variability, sensitivity to environmental conditions, and limited diagnostic capabilities. In addition, oil-based insulation systems posed significant environmental concerns due to oil aging, the need for periodic refinement or replacement, and risks associated with leakage. Fire hazards during equipment failure or explosive events further highlighted safety limitations, motivating research into alternative solid insulation materials and more scientifically grounded design methodologies in subsequent decades [25].

2.2. Mid-Century Developments (1950s–1980s)

The post-war expansion of electricity networks and increasing voltage levels drove significant innovation in stable insulation technology from the 1950s to the 1980s. One of the most crucial trends throughout this period became the introduction of epoxy resins and cast resin insulation systems [19]. Epoxy-based materials offered superior mechanical strength, good dielectric properties, and the ability to form complex geometries through casting and molding approaches. These traits made them especially appealing for dry-kind transformers, instrument transformers, bushings, and rotating machines [26, 27].

In parallel, massive progress was made in ceramic and glass insulators, especially for outdoor applications. Improved raw material processing, glazing techniques, and high-quality manipulation caused more desirable mechanical robustness, decreased porosity, and increased resistance to pollution and environmental aging. Porcelain insulators became the dominant solution for overhead strains and substation systems, profiting from standardized designs and well-mounted production approaches [28-30].

This period also marked the emergence of thermal aging concepts in insulation engineering. Systematic studies started out to quantify the connection between temperature, material degradation, and provider lifetime, leading to the method of thermal patience instructions and lifelong fashions [31-33]. Standards and guidelines are increasingly incorporating thermal aging considerations, allowing more rational insulation design and more progressive reliability evaluation. However, electric aging mechanisms, which include PDs and space charge effects, remained insufficiently understood, specifically below non-uniform electric fields [34, 35].

2.3. Late 20th Century Advances (1980s–2000s)

From the 1980s onward, rapid advances in polymer chemistry and processing technology transformed stable insulation structures in HV devices [36]. Polymer-based insulation substances, particularly cross-linked polyethylene (XLPE), emerged as the dominant solution for electricity cables because of their excellent dielectric strength, low dielectric losses, and favorable thermal performance [37, 38]. XLPE-based cables enabled higher operating voltages, reduced insulation thickness, and improved installation flexibility in comparison to traditional oil-impregnated paper cables [39].

Epoxy resin structures additionally evolved considerably throughout this era, with progressed formulations offering enhanced thermal stability, reduced shrinkage, and higher resistance to electrical aging [40]. These materials became important additives in gas-insulated switchgear (GIS), where solid spacers play an essential role in retaining mechanical integrity and electric field manage underneath compact, high-field conditions. Similar material systems are also employed in high-power rotating electrical machines, including generators and motors, where solid insulation must withstand severe electrical, thermal, and mechanical stresses. In both applications, the interaction between solid insulation surfaces and gaseous dielectrics highlighted new challenges related to surface charging and discharge initiation [41, 42].

A major milestone of this era became the creation of standardized testing techniques and PD diagnostics [43]. International requirements commenced to define uniform methods for dielectric testing, PD measurement, and aging assessment, permitting steady quality management and performance comparison throughout materials and equipment sorts [44].

By the end of the 20th century, solid insulation engineering had transitioned from an empirical layout closer to a more physics-based and standardized discipline [45]. Nevertheless, the developing complexity of HV structures, mixed with the emergence of HVDC transmission and compact device designs, discovered new limitations in traditional insulation substances, putting the level for nanocomposites, advanced diagnostics, and multifunctional insulation systems in the 21st century [46, 47].

3. Solid Insulation Materials in Modern HV Equipment

Solid insulation substances form the structural and electrical backbone of HV equipment, supplying dielectric separation, mechanical support, and long-term reliability under combined electric, thermal, and environmental stresses [20]. The selection of solid insulation is strongly application-dependent and influenced by operating voltage level, electric field distribution, thermal class, and service environment. Modern HV systems employ a wide spectrum of organic, inorganic, and composite insulation substances, each with distinct benefits and barriers. This section reviews the most widely used stable insulation materials in modern-day HV equipment, with emphasis on their properties, applications, and emerging trends [25].

3.1. Inorganic and Ceramic Insulation Materials

Inorganic insulation materials, including porcelain, glass, and superior ceramics, have long been used in HV systems due to their high-quality thermal balance, excessive compressive strength, and resistance to environmental aging [48]. Porcelain and glass insulators are generally employed in overhead transmission line insulators, bushings, and support structures. Ceramic substances exhibit exceptional resistance to thermal and electrical pressure but suffer from brittleness and high weight, restricting their use in compact and lightweight designs [49]. As a result, their application is increasingly restricted to areas of interest in which high thermal or mechanical durability is needed. In modern-day HV systems, inorganic insulation substances are regularly replaced or complemented by polymeric or composite alternatives. Nevertheless, their confirmed long-term performance ensures continued relevance in specific applications, mainly in harsh environments [50, 51].

In addition, recent developments in material processing and surface engineering have led to incremental improvements in the performance of inorganic and ceramic insulators [52]. Advanced glazing techniques, composite ceramic designs, and surface treatments have been introduced to enhance pollution resistance and reduce maintenance requirements in contaminated or coastal environments [53]. In some high-stress applications, ceramic insulators continue to offer superior dimensional stability and resistance to ultraviolet radiation, chemical exposure, and extreme thermal cycling compared to polymer-based alternatives [54]. Consequently, rather than being fully displaced, inorganic insulation materials are increasingly integrated into hybrid insulation systems or retained in strategically critical components where long-term reliability and minimal aging are paramount. Their role in modern HV equipment thus remains complementary, supporting system robustness in applications where environmental severity [55].

3.2. Cellulose-Based Insulation Systems

Cellulose-based insulation remains one of the most significantly used solid insulation structures in high-voltage power transformers and bushings due to its super dielectric performance, mechanical strength, and compatibility with liquid insulation media. Conventional insulation substances encompass kraft paper, pressboard, and thermally upgraded cellulose paper [56, 57].

In oil-immersed transformers, cellulose paper and pressboard serve as the primary solid insulation, forming turn-to-turn, layer-to-layer, and barrier insulation [58]. Their porous structure permits powerful impregnation with mineral oil or ester fluids, resulting in a composite insulation device with high dielectric energy. Thermally upgraded cellulose, changed via chemical components or molecular structure alteration, offers improved resistance to thermal aging and allows operation at higher temperatures in comparison to conventional kraft paper [59, 60].

Despite their widespread use, cellulose-based insulation systems are at risk of degradation through thermal aging, moisture ingress, and oxidation. The depolymerization of cellulose chains ends in a decrease in mechanical strength and degree of polymerization, ultimately restricting transformer lifetime. Consequently, substantial research has focused on aging diagnostics, moisture management, and the improvement of opportunity or hybrid insulation structures to enhance long-term reliability [61, 62].

3.3. Epoxy Resin Systems

Epoxy resin structures are extensively used in modern HV gadgets, especially in gas-insulated switchgear (GIS), gas-insulated lines (GIL), dry-type transformers, and insulators [41]. Both filled epoxies and cycloaliphatic epoxy resins are normally used due to their high mechanical properties, tremendous adhesion, and good dielectric properties [63]. Filled epoxy systems comprise inorganic fillers, including silica or alumina, to improve mechanical robustness, thermal conductivity, and resistance to PD. Cycloaliphatic epoxies, specifically, exhibit superior resistance to electrical tracking and surface erosion, making them appropriate for high electric-field environments. These materials are extensively used for spacers, insulators, and assist systems in GIS/GIL systems [64-66].

However, epoxy resins are inherently brittle and vulnerable to cracking under thermal cycling and mechanical strain. Additionally, their long-term overall performance may be affected by space charge accumulation, electrical treeing, and interfacial degradation between the resin and fillers. These limitations have prompted the improvement of epoxy systems, along with nanofilled and hybrid resin formulations [67, 68].

3.4. Polymeric Insulation Materials

Polymeric insulation substances play a dominant function in power cable structures and outdoor HV insulation because of their flexibility, high dielectric strength, and resistance to environmental stress. Cross-linked polyethylene (XLPE) and ethylene propylene rubber (EPR) are the most extensively used substances for medium- and high-voltage cable insulation [69, 70]. XLPE is preferred for its low dielectric loss, high breakdown strength, and desirable thermal stability, making it appropriate for each AC and DC cable system. EPR, alternatively, gives advanced flexibility and resistance to moisture and thermal aging, and is often used in applications requiring enhanced mechanical compliance [38].

Silicone rubber is extensively used in outdoor insulation, such as composite insulators and cable accessories [71]. Its hydrophobic surface properties notably reduce pollution-related flashover hazard, while its flexibility and UV resistance make it suitable for harsh environmental conditions. Nevertheless, polymeric insulation substances are sensitive to space charge effects, electric aging, and environmental degradation, mainly under HVDC operation [72, 73].

3.5. Thermoplastic and Recyclable Polymers

The growing emphasis on sustainability and environmental impact has driven interest in thermoplastic and recyclable polymers for HV insulation applications. Polypropylene-based insulation structures have emerged as promising options to conventional cross-linked materials, mainly for HVDC cable applications [74, 75].

Thermoplastic polypropylene gives benefits including recyclability, lower dielectric losses, and reduced space charge accumulation in comparison to XLPE. Its melt-processability additionally permits easier production and end-of-life recycling [76]. These properties align well with the increasing demand for sustainable and environmentally friendly insulation substances in modern power systems. Despite these benefits, demanding situations continue to be in accomplishing long-term thermal stability, mechanical robustness, and compatibility with existing cable production approaches. Ongoing research specializes in polymer blends, components, and structural modifications to overcome these barriers [77, 78].

3.6. Nanocomposite and Hybrid Insulation Systems

Nanocomposite insulation structures constitute a great advancement in dielectric materials. Polymer nanodielectrics, incorporating nanofillers such as silica, alumina, graphene, or layered silicates, have demonstrated improved dielectric strength, reduced area charge accumulation, and improved resistance to PD and electric aging [79, 80].

By tailoring the filler type, concentration, and interfacial chemistry, nanocomposites provide the capacity to decouple historically competing properties such as mechanical strength and dielectric performance. These materials are increasingly investigated for use in cables, spacers, and insulation obstacles in advanced HV devices [81]. Hybrid structures, along with resin-impregnated paper (RIP) and resin-impregnated synthetic (RIS) insulation, integrate the advantages of cellulose or synthetic fibrous structures with epoxy resins. RIP and RIS structures are extensively used in HV bushings because of their excessive mechanical integrity and improved moisture resistance as compared to oil-impregnated paper structures [82, 83].

Despite these promising advantages, the large-scale implementation of nanocomposite and hybrid insulation systems in HV equipment still faces several challenges. Achieving uniform nanofiller dispersion, ensuring long-term interfacial stability, and maintaining reproducibility in industrial manufacturing processes remain critical issues [84]. In addition, the long-term aging behavior of nanodielectrics under combined electrical, thermal, and environmental stresses is not yet fully understood, particularly under HVDC operating conditions where space charge dynamics play a dominant role. For hybrid systems such as RIP and RIS, interfacial compatibility, resin curing-induced stresses, and PD resistance at material interfaces require further optimization [85-87]. Consequently, while nanocomposite and hybrid insulation systems represent a promising pathway toward next-generation HV insulation, their widespread adoption will depend on continued advances in material design, processing control, and physics-based lifetime assessment methodologies [86].

4. Dielectric, Thermal, and Mechanical Properties of Solid Insulation

The performance and reliability of stable insulation structures in HV equipment are ruled by a complex interaction of dielectric, thermal, and mechanical properties. These properties decide not only the preliminary face up to functionality of insulation substances but also their long-term balance under mixed electric, thermal, mechanical, and environmental stresses. A comprehensive expertise of those traits is therefore vital for fabric selection, insulation layout, and lifetime evaluation of HV equipment.

4.1. Permittivity and Conductivity Behavior

Relative permittivity and electrical conductivity are fundamental parameters that without delay influence electrically powered subject distribution within insulation systems. In composite insulation systems normally utilized in transformers, cables, and bushings, mismatches in permittivity between exclusive materials can cause localized electric subject enhancement, increasing the threat of PD inception and extended aging [88, 89]. Traditional cellulose-based insulation generally reveals mild permittivity values ($\varepsilon_r \approx 3$ –

4), while polymeric substances, which include polyethylene (PE), XLPE, and polypropylene (PP), commonly exhibit lower permittivity, contributing to more uniform electric field distributions in cable insulation [90].

Electrical conductivity in solid dielectrics strongly depends on temperature, electric field intensity, moisture content, and material morphology. Under AC conditions, conductivity mainly contributes to dielectric losses, whereas below direct current DC or combined AC/DC fields, it will become a dominant issue in space charge dynamics and electric field distortion [91]. In HVDC devices, insulation materials with nonlinear conductivity behavior are frequently favored, as area-dependent conductivity can help redistribute electric stress more uniformly. Recent research has validated that polymer nanocomposites, incorporating inorganic fillers along with silica or alumina, may be engineered to tailor permittivity and suppress immoderate conductivity by using deep charge traps at the polymer–filler interface [4, 92].

4.2. Breakdown Strength and Space Charge Effects

Dielectric breakdown strength is a critical overall performance metric for solid insulation, defining the maximum electric subject that material can withstand without catastrophic failure [92]. Breakdown mechanisms in solids are inspired by intrinsic material properties, defects, electrode configuration, and environmental situations [93]. In polymeric insulation, breakdown frequently initiates from localized susceptible points together with voids, impurities, or interfacial regions, in which electrical stress is concentrated. Epoxy resins and polymer composites typically indicate excessive intrinsic breakdown electricity, but their overall performance can degrade substantially in the presence of manufacturing defects or aging-prompted microstructural adjustments [20, 94].

Space charge accumulation has emerged as a key issue for solid insulation beneath HVDC and long-period DC pressure. Injected charges from electrodes or generated in the bulk can accumulate at interfaces or in trap sites, leading to excessive electric field distortion and localized overstressing [95, 96]. This phenomenon is especially prevalent in polymeric substances with extremely low conductivity, including XLPE. Space charge results now not only reduce powerful breakdown strength but also boost electrical aging via a more advantageous rate of injection and localized heating. Advanced fabric solutions, together with nanocomposites, multilayer insulation structures, and functionally graded dielectrics, were proposed to mitigate space charge accumulation by means of controlling trap depth and charge mobility[97-99].

4.3. Surface Versus Bulk Insulation Performance

In practical HV equipment, insulation failure frequently initiates at surfaces or interfaces in preference to within the bulk material (Figure 1). Surface insulation overall performance is governed by surface conductivity, roughness, contamination, and environmental factors, along with humidity and pollution [100]. Surface discharges, which include corona and floor tracking, can gradually erode insulation and cause a flashover, especially in outside or fuel-insulated structures. Hydrophobic polymeric substances, such as silicone rubber, are extensively used in outdoor insulators because of their capacity to suppress floor leakage currents and maintain performance in polluted situations [101]. Bulk insulation overall performance, alternatively, is dominated by intrinsic material properties and inner defect structures. Bulk degradation mechanisms consist of electric treeing, thermal decomposition, and mechanical fatigue, which evolve over long service intervals [71]. In complex insulation systems combining multiple substances, such as oil-impregnated paper or epoxy-impregnated pressboard, interfaces play a vital role in figuring out both surface and bulk behavior. Poor interfacial bonding can facilitate PD initiation and moisture ingress, appreciably decreasing dielectric strength [102, 103].

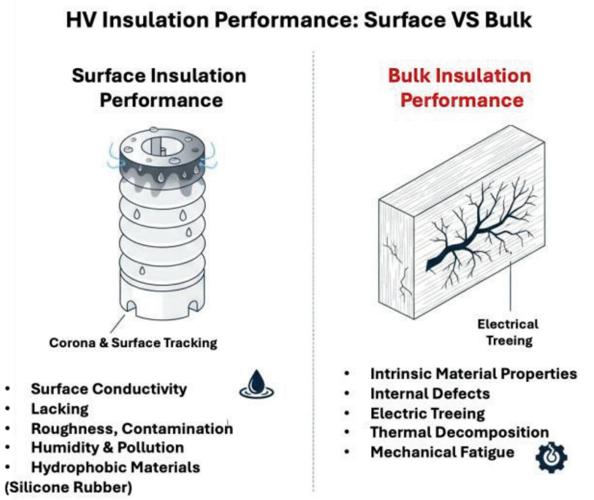

Figure 1: Surface vs. Bulk Insulation Performance and Failure Modes.

4.4. Thermal and Mechanical Considerations

Thermal performance is carefully connected to dielectric behavior, as increased temperatures accelerate chemical degradation, increase electric conductivity, and reduce breakdown strength [32].

Solid insulation substances need to therefore showcase enough thermal persistence to face up to non-stop operation and brief overload situations. Cellulose-based insulation is particularly sensitive to thermal aging, with depolymerization leading to a loss of mechanical properties and decreased dielectric performance [56]. In assessment, contemporary thermoplastic polymers and epoxy systems offer advanced thermal stability, allowing better running temperatures and multiplied energy density in compact system designs [104, 105].

Mechanical properties, along with tensile strength, elasticity, and resistance to creep and fatigue, are similarly important for ensuring long-term insulation integrity [106]. Solid insulation substances regularly serve a dual characteristic as both electric insulators and structural components, helping windings and maintaining clearances under electromechanical forces [107]. Thermal enlargement mismatch among specific substances can set off mechanical stresses during temperature cycling, leading to cracking, delamination, or interfacial degradation. Advanced composite materials and functionally graded insulation systems are an increasing number of employed to achieve mechanical robustness with optimized dielectric and thermal performance [108, 109].

5. Aging Mechanisms and Degradation Phenomena

Aging mechanisms and degradation phenomena in solid insulation systems are governed by a complicated aggregate of thermal, electrical, mechanical, and environmental factors that progressively deteriorate material performance over the years (Figure 2) [110]. Among those, thermal aging is one of the most fundamental tactics influencing the lifetime of insulating substances. Elevated temperatures accelerate chemical reactions within polymers and composite insulation structures, leading to bond scission, oxidation, and depolymerization [21]. In cellulose-based insulation, together with paper and pressboard used in transformers, thermal aging causes a reduction in the degree of polymerization, resulting in a loss of mechanical strength and dielectric integrity. In polymeric insulators, prolonged thermal exposure can result in chain relaxation, crystallinity modifications, and the formation of low-molecular-weight byproducts, all of which increase dielectric losses and reduce breakdown strength. Thermal aging is mainly important under continuous excessive-load operation or throughout short-time period overloads, wherein localized hotspots may also form and provoke untimely failure[92, 111, 112].

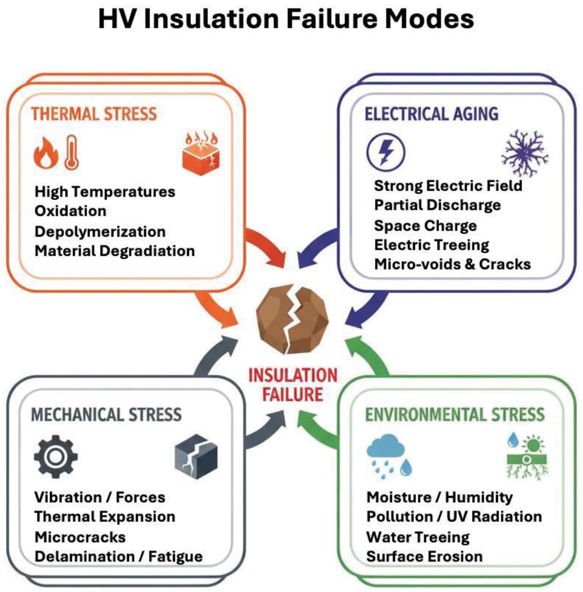

Figure 2: Multi-Physics Degradation Pathways in High-Voltage Insulation

Electrical aging represents any other dominant degradation pathway, especially in HV systems, wherein strong electric fields are present [113]. Long-time exposure to electrical stress can result in charge injection, space charge accumulation, and localized field enhancement inside solid dielectrics. Partial discharges play an imperative role in this system, as they generate high-energy electrons, ultraviolet radiation, and reactive chemical species that attack the insulation surface and bulk. Over time, PD activity results in erosion, electrical treeing, and the formation of micro-voids and cracks [114-116]. These defects further intensify nearby electric fields, growing a self-accelerating degradation cycle. In polymeric substances, electric tree increase is regularly accompanied by chemical degradation and carbonization along tree channels, ultimately ensuing in catastrophic breakdown. Even in superior materials consisting of epoxy resins and silicone rubbers, sustained electric aging can notably shorten carrier life if not properly controlled through layout and material selection [117].

Mechanical and environmental stresses additionally make notable contributions to insulation aging, often performing in conjunction with thermal and electrical elements. Mechanical stresses might also arise from vibration, electromagnetic forces, or thermal growth mismatch between unique components in composite insulation systems [118, 119]. Repeated mechanical loading can provoke microcracks and interfacial debonding, in particular in fiber-reinforced composites and laminated systems. Environmental elements, consisting of humidity, pollution, ultraviolet radiation, and chemical contaminants, in addition to exacerbating degradation [120]. Moisture ingress is specifically damaging because it will increase dielectric permittivity and conductivity at the same time as decreasing breakdown voltage. In cellulose-based insulation, moisture accelerates hydrolytic aging, while in polymeric substances, it may promote water treeing. Outdoor insulation systems are additionally exposed to UV radiation and pollutants, which could lead to surface degradation, erosion, and a lack of hydrophobicity [121, 122].

In real working situations, aging hardly ever happens because of a single strain factor; instead, it is the end result of complicated multi-physics interactions [123]. Thermal, electric, mechanical, and environmental stresses are strongly coupled and regularly amplify each other's outcomes. For example, thermal aging can increase electrical conductivity and dielectric losses, which in turn improve local temperatures beneath electric strain [124]. Similarly, electric discharges can generate localized heating and mechanical shock, accelerating each thermal and mechanical degradation. Moisture and contaminants not only weaken dielectric strength but also modify the electric discipline distribution, increasing the likelihood of PD inception [32]. These synergistic interactions make aging conduct highly nonlinear and tough to predict using single-stress models. As a result, modern lifetime assessment strategies increasingly rely on multi-stress testing and advanced diagnostic techniques to capture the combined effects of aging mechanisms. Understanding those multi-physics degradation processes is critical for the development of more dependable insulation systems and for extending the service life of high-voltage devices under increasingly severe operating conditions [79, 104].

6. Emerging Challenges in HVDC and UHV Systems

The rapid expansion of HVDC and ultra-high-voltage (UHV) transmission systems has introduced increasingly demanding operating conditions for solid insulation materials, which are required to function under very high electric field stresses. For instance, in conventional power cables the maximum operating electric field typically lies in the range of a few kV/mm, whereas in extra-high-voltage (EHV) and UHV cable systems, it can reach several tens of kV/mm[124-126]. While HVDC and UHV technologies provide significant benefits in terms of long-distance energy transmission, grid interconnection, and integration of renewable energy resources, the operation situations imposed on insulation substances are appreciably more demanding. In particular, the presence of constant or slowly varying electric fields, higher voltage levels, and complicated thermal and environmental stresses fundamentally adjust insulation behavior and aging mechanisms [127, 128].

One of the most crucial challenges in HVDC insulation systems is space charge accumulation inside an insulation. Under DC electric fields, charge injection from electrodes and charge delivery in the fabric can result in the buildup of space charge, which distorts the internal electric field distribution [129]. Unlike HVAC systems, where periodic discipline reversal limits long-term charge accumulation, HVDC operation allows charges to persist and accumulate over time [45]. This can result in extreme localized electric field enhancement, accelerating electric aging, and increasing the risk of breakdown. Space charge effects are specifically suggested in polymeric insulation substances, such as XLPE and epoxy structures, that are broadly used in HVDC cables and equipment [130].

Polarity reversal and field inversion represent additional challenges unique to HVDC systems. During operational events such as power flow reversal, converter faults, or maintenance procedures, the polarity of the applied voltage may change, causing a sudden redistribution of space charge within the insulation [131]. This transient condition can lead to extreme electric field enhancement at material interfaces or near electrodes, significantly exceeding steady-state stress levels. Repeated polarity reversals can therefore impose severe electrical and mechanical stress on insulation systems, promoting crack initiation, interfacial debonding, and accelerated degradation. These phenomena are especially critical in UHV applications, where the absolute field levels are already close to material performance limits[132, 133].

As a result of those demanding situations, insulation substances for HVDC and UHV structures need to meet performance necessities that extend beyond those historically taken into consideration for HVAC operation [134]. In addition to high dielectric strength and thermal balance, insulating materials ought to showcase low-frequency injection, decreased charge mobility, and strong resistance to space charge accumulation [135]. Long-term electric conductivity balance, resistance to electro-thermal aging, and strong interfacial properties are critical. Furthermore, insulation systems must preserve reliable performance below mixed stresses, together with high electric fields, temperature gradients, mechanical stresses, and environmental exposure [136]. Addressing these rising demanding situations calls for not only the development of advanced materials and composites but also improved testing methodologies and design tactics that replicate the unique multi-physics situations of HVDC and UHV operation [137].

7. Sustainability and Environmental Considerations

Sustainability has become a crucial design driving force in modern HV insulation systems, driven by increasing environmental regulations, weather commitments, and the need for long-term useful resource performance in power infrastructure [14]. Traditional insulation solutions, mainly oil-impregnated cellulose structures, have demonstrated reliable overall performance over many years; but, their environmental footprint, dependence on fossil-based resources, and end-of-life demanding situations have stimulated the development of greater sustainable alternatives. As a result, contemporary studies increasingly focus on recyclable materials, reduced oil dependence, and lifestyle-cycle-oriented eco-design strategies [138, 139].

One of the most promising directions is the development of recyclable and reusable solid insulation substances. Thermoplastic polymers, including PE, PP, and their advanced derivatives (e.g., XLPE options and recyclable elastomers), offer giant advantages over thermoset materials due to their reprocessability [140]. Unlike cross-linked or epoxy- based systems, thermoplastics can be melted and reformed, permitting fabric recovery at the end of service life. Recent advances in high-temperature and high-dielectric-performance thermoplastics have made them possible applicants for medium- and high-voltage programs, which include cables, bushings, and auxiliary insulation additives [10]. In addition, bio- based polymers and natural fiber-reinforced composites are being explored as partial replacements for petroleum-based materials, presenting decreased carbon footprints while retaining ideal electric and mechanical performance [141].

Reducing oil dependence on insulating oils is another key sustainability objective. Mineral oil, broadly utilized in transformers and other high-voltage systems, poses environmental risks related to leakage, flammability, and disposal [142]. In response, alternative answers, including herbal ester fluids, synthetic esters, and dry-type or strong-insulated systems, have gained attention [143]. Natural esters, derived from renewable vegetable resources, exhibit excessive biodegradability and improved fire protection as compared to mineral oils. Moreover, the transition in the direction of oil-free or oil-reduced designs, including cast-resin transformers and stable-dielectric DC devices, appreciably lowers environmental risks and maintenance requirements. These processes are mainly attractive for city, offshore, and environmentally sensitive installations [144-146].

Life-cycle assessment (LCA) and eco-design ideas offer a complete framework for comparing the environmental impact of insulation structures from raw material extraction to end-of-life control [147]. LCA studies have proven that fabric selection, carrier lifetime, and recyclability strongly have an impact on the general environmental footprint of HV equipment [148]. Designing insulation structures for extended operational existence, decreased losses, and stepped forward growing old resistance not only complements reliability but additionally minimizes aid consumption and waste generation. Eco-design strategies further emphasize modularity, ease of disassembly, and compatibility with recycling techniques, enabling greater sustainable asset management [149].

Therefore, sustainability considerations are reshaping the development of solid insulation systems in HV engineering. The integration of recyclable materials, reduced reliance on insulating oils, and life-cycle-oriented design approaches are essential for achieving environmentally responsible and future-proof power infrastructure. Continued interdisciplinary research combining materials science, electrical engineering, and environmental assessment will play a pivotal role in advancing sustainable insulation technologies.

8. Research Gaps and Future Directions

Despite vast advances in solid insulation substances and diagnostic technologies, numerous important study gaps continue to exist that must be addressed to ensure the dependable deployment of subsequent-technology HV insulation systems. As power networks continue to evolve toward higher voltage level, elevated energy density, and more complicated operation conditions, future research must focus on long-term material performance, essential aging mechanisms, standardization issues, and the translation of laboratory findings to real HV devices.

One of the most prominent research gaps concerns the long-term performance of polymer nanocomposites used in HV insulation. While numerous studies have demonstrated improved dielectric power, PD resistance, and space charge suppression at the laboratory scale, the durability of these improvements over a long time is insufficiently understood. Nanoparticle dispersion balance, agglomeration under thermal and electric stress, and potential modifications in interfacial chemistry over the years may considerably have an effect on insulation reliability. Accelerated aging checks frequently fail to absolutely replicate the mixed electrical, thermal, mechanical, and environmental stresses encountered in service, highlighting the need for long-period experiments and established aging models.

An associated challenge lies in the knowledge of the physics of interface growing older in multi-material insulation structures. Interfaces among polymers, fillers, electrodes, and impregnating media regularly represent the weakest factors in insulation systems. Charge trapping, chemical degradation, moisture ingress, and thermo-mechanical mismatch at interfaces can result in localized field enhancement and untimely failure. Although enormous development has been made in characterizing interfacial phenomena using advanced diagnostic strategies, a complete, physics-based framework linking microscopic interface strategies to macroscopic insulation failure continues to be lacking. Bridging this gap is important for the dependable design of composite and hybrid insulation systems, in particular for HVDC programs wherein space charge consequences are stated.

Standardization presents some other foremost challenges for rising insulation materials and virtual diagnostic processes. Existing worldwide requirements are, in large part, primarily based on conventional substances and established test methods, which might not adequately capture the behavior of novel substances, including nanocomposites, recyclable thermoplastics, or bio-based insulations.

Finally, scaling laboratory results to real HV equipment remains a persistent challenge. Many promising insulation concepts demonstrate excellent performance in small-scale specimens but encounter unforeseen issues when applied to full-scale components due to manufacturing variability, geometric complexity, and operational constraints. Future research should emphasize multi-scale modeling, pilot-scale testing, and close collaboration between academia, manufacturers, and utilities to bridge the gap between laboratory innovation and practical implementation. Addressing these challenges will be key to realizing reliable, sustainable, and intelligent insulation systems for future power networks.

9. Conclusions and Outlook

The historical development of solid insulation systems in HV engineering has been driven by the continuous need for higher reliability, increased voltage levels, and improved safety margins. From traditional oil-impregnated cellulose and ceramic insulators to modern polymeric and composite materials, each generation of insulation has reflected advances in materials science, manufacturing techniques, and understanding of aging mechanisms. Key lessons from this evolution highlight the importance of multi-stress endurance, robust interface design, and conservative validation under realistic operating conditions to ensure long-term performance. Despite significant progress, current solid insulation systems still face notable limitations. Aging under combined electrical, thermal, mechanical, and environmental stresses remains a major challenge, particularly for polymer-based materials and complex multi-material interfaces. Issues such as space charge accumulation, PD activity, and moisture sensitivity can limit lifetime and reliability, especially in HVDC and power electronic applications. Looking ahead to the next 10–20 years, solid insulation systems are expected to evolve toward more sustainable, intelligent, and application-specific solutions. Advances in nanocomposites, recyclable materials, and bio-based insulations will enable improved reliability and lifecycle management. Continued integration of materials research, modeling, and field experience will be essential for developing future-proof insulation systems that support the transformation of global power networks.

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