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**Research Paper**

# Recent Advances in Nanodielectrics for High-Voltage Electrical Insulation: From Material Design to Practical Applications in Power Apparatus – A Comprehensive Review

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***Abstract***
*Nanodielectrics mark a significant leap forward in high-voltage (HV) insulation technology, bringing substantial improvements compared to traditional epoxy resins. These advancements include higher dielectric breakdown strength, better resistance to partial discharges, suppression of electrical treeing, and enhanced thermal conductivity. This review consolidates major developments from 2023 to 2026, with a focus on epoxy-based nanocomposites incorporating nanofillers like* $SiO_2$*,* $Al_2O_3$*, BN,* $TiO_2$*, graphene oxide, and hybrid combinations. Reported enhancements typically range from 15–37% improvement in AC/DC breakdown strength, reduced space charge accumulation, and thermal conductivities reaching 0.9–10 W/m·K. The discussion covers fabrication techniques, interfacial engineering guided by Tanaka's multi-core model, property optimization, as well as applications in cast-resin transformers, GIS spacers, circuit breakers, and HVDC cables. Key challenges such as scalability, long-term performance under multi-stress conditions, standardization issues, and sustainability are critically analyzed. Future directions emphasize the integration of AI-assisted design, self-healing materials, and bio-based formulations to address these challenges. The paper also highlights educational implications for the Faculty of Electrical Engineering at Thai Nguyen University of Technology to align with Vietnam's goals for advancing its smart grid infrastructure and transitioning to* $SF_6$*-free technologies.*

***Keywords:*** *nanodielectrics, epoxy nanocomposites, high-voltage insulation, electrical treeing, partial discharge, GIS spacers, thermal conductivity, interfacial region.*

## I. Introduction

The global electrical power industry is undergoing a profound transformation, driven by the increasing integration of renewable energy sources, rapid urbanization, and the growing need for higher transmission capacities. In Vietnam, the expansion of the national power grid is marked by significant developments, including the construction of 500 kV transmission lines and the adoption of high-voltage direct current (HVDC) systems to accommodate large-scale solar and wind energy projects. This infrastructural growth imposes rigorous demands on electrical insulation materials, which must endure extreme electric fields, thermal stresses, and challenging environmental conditions while ensuring long-term reliability and the compactness of modern equipment. Traditionally, epoxy resins derived from diglycidyl ether of bisphenol A (DGEBA) have served as the cornerstone of electrical insulation for cast-resin transformers, gas-insulated switchgear (GIS) spacers, bushings, and circuit-breaker components. These materials are recognized for their excellent mechanical properties, ease of processing through casting or molding, and sufficient dielectric strengths under moderate operating conditions. However, the limitations of conventional epoxy resins become increasingly pronounced in high-power-density applications that operate at voltages between 110 kV and 550 kV or higher. Conventional epoxy systems often suffer from a relatively low dielectric breakdown strength under prolonged exposure to high electric fields, significant vulnerability to electrical treeing and surface tracking, low thermal conductivity (approximately 0.2 W/m·K), and substantial space charge accumulation. Such deficiencies contribute to localized electric field intensification, thermal hotspot formation, accelerated aging, and untimely insulation failures. For example, in GIS and gas-insulated line (GIL) systems, surface charge accumulation on epoxy spacers under direct current (DC) stress distorts field distribution, heightening the risk of flashover. Likewise, in cast-resin transformers and HVDC cables, inadequate heat dissipation leads to potential thermal runaways, while electrical treeing—often triggered by voids, impurities, or moisture—substantially reduces the service life of insulation systems. As designs lean toward more compact and environmentally sustainable configurations amid global plans to phase out sulfur hexafluoride ($SF_6$), the performance limitations of neat epoxy resins become critical. To address these challenges, nanodielectrics have emerged as a transformative technological solution. First systematically conceptualized by Tanaka in the early 2000s, nanodielectrics employ nanoscale inorganic or organic fillers (typically <100 nm) in low-mass fractions (0.1–5 wt%) to alter the material's properties fundamentally. A defining feature of nanodielectrics is their extensive interfacial region between the nanofiller and polymer matrix—often extending hundreds of square meters per gram of filler—which significantly enhances charge carrier dynamics, phonon interactions, and mechanical reinforcement at the molecular level. Unlike conventional microcomposites (where fillers primarily act as passive additives), nanofillers generate deep electron and ion trap sites, mitigate space charge accumulation, normalize local electric fields, and suppress electron avalanches. The benefits are considerable: dielectric breakdown strength improves by 15–50%, resistance to partial discharge increases significantly, electrical tree propagation slows, and thermal conductivity is enhanced without a proportional rise in dielectric loss. Recent years have witnessed a surge in research dedicated to epoxy-based nanodielectrics. Between 2023 and 2026, there has been a notable increase in scholarly contributions published by journals such as IET Nanodielectrics, IEEE Transactions on Dielectrics and Electrical Insulation, Energies, and Polymer Engineering & Science. These studies have explored a wide range of nanofiller materials—including silica ($SiO_2$), alumina ($Al_2O_3$), boron nitride (BN), titanium dioxide ($TiO_2$), and advanced hybrid systems—along with progressive interfacial engineering techniques such as silane coupling agents, plasma treatments, and core-shell structures. Prominent advancements have been achieved; for instance, alkyl-modified nanosilica has significantly extended the lifetime of electrical treeing resistance, while boron nitride hybrid configurations have nearly achieved thermal conductivities of 1 W/m·K while maintaining high dielectric strength. Innovative developments like multilayer gradient structures and electrostatic dispersion methods are addressing the traditional trade-offs between thermal conductivity and dielectric performance. The adoption of nanodielectric technology is particularly relevant for Vietnam's strategic goals. These include transitioning to $SF_6$-free switchgear technologies, enhancing HVDC transmission systems to facilitate renewable energy integration, and developing compact substations tailored for densely populated urban environments or challenging geographical terrains such as mountainous regions. In this context, institutions like the Faculty of Electrical Engineering at Thai Nguyen University of Technology (TNUT) play an essential role in preparing future engineers to design, develop, and maintain these advanced insulation systems. Updating university curricula—especially core courses such as Electrical Materials and Electrical Apparatus—to incorporate foundational knowledge on nanodie.

## II. Content

### 2.1 Scientific Foundations of Nanodielectrics

The exceptional performance of nanodielectrics can be attributed to the nanoscale interfacial regions that significantly influence material behavior, particularly at low filler concentrations. The foundational framework for understanding these phenomena is provided by Tanaka's multi-core model. This conceptualization delineates three distinct interfacial layers surrounding each nanoparticle: a bonded layer characterized by tightly adhered polymer chains; a loosely bound layer, where chain mobility is markedly altered; and the far-field region, which extends into the bulk matrix. These interfacial layers collectively introduce a high density of deep trap sites, with energy depths generally ranging between 1 to 2 eV, that effectively immobilize charge carriers. As a result, charge mobility is reduced, mitigating the formation of space charge clouds. Consequently, there is minimal distortion of local electric fields, an increase in the partial discharge inception voltage, and significant retardation of electrical tree propagation. Simultaneously, the dispersion of nanofillers enhances phonon transport by forming thermally conductive pathways while scattering electrons to preserve dielectric characteristics. This dual enhancement effectively addresses the long-standing trade-off between thermal conductivity and dielectric properties. Moreover, surface functionalization, achieved through methods such as silane coupling agents, polymer grafting, or plasma activation, plays a key role in fortifying interfacial bonding, mitigating filler agglomeration, and optimizing the distribution of trap sites. Empirical studies conducted between 2024 and 2026 corroborate that these interfacial mechanisms yield remarkable improvements, including 30–70% reductions in space charge density (as measured by pulsed electro-acoustic techniques) and narrower Weibull distributions in breakdown data—an indication of enhanced reliability. Additionally, under synergistic stresses, the interfacial regions augment resistance to moisture ingress and oxidative degradation, thereby extending insulation lifespan in tropical climates like those prevalent in Vietnam. These principles form the backbone for advancements in the fabrication processes, property optimization, and applications of nanodielectrics.

### 2.2. Fabrication Methods, Nanofiller Types, and Property Enhancements

Fabrication methods for high-performance epoxy-based nanodielectrics necessitate meticulous control over both nanoparticle dispersion and interfacial compatibility. Standard practices involve modifying nanofillers via silane coupling agents and polymer grafting techniques to improve their wettability and prevent agglomeration. Dispersion approaches include ultrasonication, high-shear mixing, three-roll milling, and in-situ sol-gel synthesis—processes often followed by vacuum degassing and thermal or ultraviolet curing steps. While two-step masterbatch methods are preferred for large-scale manufacturing due to their practicality, one-step in-situ polymerization demonstrates superior interfacial quality. Cutting-edge strategies such as direct current field-induced alignment and electrostatic dispersion enable the creation of anisotropic or gradient microstructures, thus enhancing thermal transport and electrical insulation properties simultaneously. Extensive research has been conducted on a variety of nanofiller materials. Silica ($SiO_2$), for instance, provides substantial improvements in breakdown strength (15–20%) and electrical treeing resistance; alkyl-modified derivatives have showcased remarkable durability against treeing phenomena. Alumina ($Al_2O_3$) offers notable effectiveness in suppressing partial discharges and has found use in gas-insulated switchgear spacers. In certain dual-interface configurations featuring alumina, alternating current (AC) breakdown strengths as high as 37.5 kV/mm and direct current (DC) ratings of up to 67.8 kV/mm have been achieved. Furthermore, boron nitride (BN) and aluminum nitride (AlN) hybrids facilitate the construction of three-dimensional phonon networks that raise thermal conductivity to approximately 1 W/m·K while preserving dielectric properties. Nanocarbon materials such as graphene oxide and carbon nanotubes, even at ultra-low loadings (0.1–0.5 wt%), demonstrate customizable dielectric performance when appropriately functionalized. Innovative hybrid systems as well as core-shell architectures exhibit synergistic performance enhancements by combining attributes such as mechanical robustness, efficient thermal transport, and advanced charge-trapping capabilities. Recent advancements in multilayer gradient composites have overcome traditional material trade-offs; specific systems now achieve breakdown strengths surpassing 100 kV/mm while maintaining elevated levels of thermal conductivity. Such material innovations translate directly into significant property enhancements across multiple domains. Electrical attributes benefit from increased breakdown fields (a 15–37% improvement), lowered space charge accumulation, diminished dielectric losses ($\tan \delta < 0.01$), and enhanced resistance to partial discharge phenomena, surface tracking, and erosion. In terms of thermal properties, composites embedded with boron nitride achieve thermal conductivity amplification by factors ranging from 3 to as high as 50, alongside elevated glass transition temperatures and improved oxidative stability. Mechanically speaking, robust interfacial adhesion contributes to gains in tensile strength, elastic modulus, and toughness while inhibiting crack propagation at microscale defects. Weibull statistical analysis consistently demonstrates higher shape parameters for breakdown performance profiles, signifying improved reliability metrics. Collectively, these gains enable more compact, efficient, and durable high-voltage components.

### 2.3. Applications in High-Voltage Power Equipment

Nanodielectric materials have evolved from niche experimental substances into integral components of various high-voltage electrical systems, offering transformative advancements in their design and performance. In cast-resin transformers, the application of nanodielectric bushings and winding insulation provides significant benefits, including enhanced moisture resistance, improved flame retardancy, and superior thermal management capabilities. These attributes not only enable the development of transformers with higher power ratings but also allow for reductions in physical dimensions. The increased thermal conductivity of these materials mitigates hotspot temperatures, improving overload tolerance and extending operational lifespan, especially in the context of fluctuating renewable energy load demands. In the realm of gas-insulated switchgear (GIS) and gas-insulated lines (GIL), epoxy-based nanocomposite spacers deliver critical performance enhancements when subjected to direct current (DC) stresses. These spacers minimize surface charge accumulation, facilitate a more uniform distribution of the electric field, and support the transition to compact, environmentally friendly $SF_6$-free systems operating in the 420 kV to 550 kV voltage range. Initial industry implementations have demonstrated notable advancements, including a reduction in equipment size by 20–30% and improved impulse withstand voltage capabilities. Similarly, for circuit breakers, the deployment of nanodielectric materials enhances dielectric recovery following arc extinction while simultaneously improving mechanical durability. In high-voltage direct current (HVDC) cables and associated accessories, the introduction of cross-linked polyethylene (XLPE)-based or epoxy nanocomposites has proven effective in suppressing electrical treeing and addressing stresses related to polarity reversals. This innovation supports higher operational voltage levels and facilitates long-distance power transmission, a critical requirement for renewable energy integration. Furthermore, instrument transformers, such as current and voltage transformers, greatly benefit from heightened resistance to partial discharges, ensuring accurate metering performance and reliable operation under high-stress conditions. Additionally, nascent applications of nanodielectric insulation are emerging in fast-charging infrastructure for electric vehicles and medium-voltage DC distribution systems, where compact designs and rapid switching capabilities are crucial. Field trials and pre-commercial prototypes anticipated between 2024 and 2026 underscore the potential of nanodielectric technologies to not only enhance system performance but also promote environmental sustainability by enabling the production of smaller, lighter, and more resource-efficient equipment. In Vietnam, the integration of these advanced materials offers promising opportunities to accelerate the development of resilient 500 kV power infrastructure. Moreover, it paves the way for domestic innovation by fostering collaborations between academic institutions and industrial stakeholders aimed at advancing the production of high-performance insulation components.

### 2.4. Challenges and Future Perspectives

While nanodielectrics have demonstrated significant potential in laboratory settings, several critical challenges must be addressed before they can achieve broad industrial deployment. One major hurdle lies in achieving uniform dispersion of nanofillers at manufacturing scales. Current techniques, such as high-shear mixing and ultrasonic methods, require significant energy input and struggle to ensure consistency for large-scale processes like casting or extrusion. When filler loadings exceed 3 wt%, particle agglomeration tends to occur, creating defect sites that ironically compromise breakdown strength. Additionally, the high costs associated with surface-modified nanofillers and specialized processing equipment result in material prices that are 30–100% higher compared to regular epoxy systems. Another key challenge is the lack of sufficient understanding of long-term performance under complex, real-world conditions. While much effort has been devoted to short-term AC/DC breakdown studies, critical data on aging over decades—under simultaneous exposure to factors such as high temperatures, humidity, electrical fields, mechanical vibrations, and chemical contaminants—remain limited. Stressors like thermal cycling, DC polarity reversals, and superimposed harmonics further complicate performance prediction. Existing accelerated aging models that account for interfacial degradation, filler-matrix debonding, and moisture-induced hydrolysis still require extensive validation through combined electrical-thermal-mechanical test protocols. A third obstacle is the absence of standardized testing methodologies tailored specifically to nanocomposites. Existing certification systems based on IEC and IEEE standards often fall short because they were designed for microcomposites or unmodified polymers, failing to consider unique nanoscale interfacial effects. This gap results in inconsistent qualification outcomes across laboratories. Reproducibility between research groups is also hampered by minor yet influential differences in filler surface chemistry or curing processes, which can significantly impact properties like charge-trap distributions. Environmental and sustainability concerns present yet another layer of difficulty. Many nanofillers pose challenges related to toxicity and recyclability at the end of their lifecycle. The epoxy matrix itself typically relies on fossil-derived components, and while bio-based alternatives reinforced with nanocellulose or lignin-derived fillers show promise, they remain in early development stages. Additionally, regulatory pressures to eliminate the use of sulfur hexafluoride ($SF_6$) compel the search for insulation materials that are both environmentally safe and compatible with alternative gases. Despite these challenges, various promising advancements could help overcome these barriers. Artificial intelligence and machine-learning tools are increasingly being applied to improve interfacial chemistries, model aging behaviors, and expedite the virtual screening of countless filler-matrix combinations. Self-healing nanodielectrics that leverage microcapsules or dynamic covalent bonds offer the potential for autonomous repair of electrical trees, which could significantly extend service lifetimes. Multifunctional smart materials with built-in sensing capabilities also enable real-time monitoring of key electrical equipment such as gas-insulated switchgear (GIS) and transformers. Hybrid systems that integrate nanodielectrics with wide-bandgap semiconductor coatings or cryogenic cooling technologies hold promise for applications in ultra-high-voltage DC and compact medium-voltage DC systems. Furthermore, adopting circular-economy principles by designing fully recyclable nanocomposites and implementing environmentally conscious synthesis processes will help align these materials with global decarbonization efforts. In the context of Vietnam, these innovations are particularly relevant as they could support national initiatives such as the 500 kV grid upgrade and the roadmap for phasing out $SF_6$ gas. Achieving this will require substantial enhancements in local manufacturing capacity, which can be facilitated through collaborative partnerships between universities and industry players.

### 2.5. Implications for Education and Training in Electrical Engineering at Thai Nguyen University of Technology

At the Faculty of Electrical Engineering at Thai Nguyen University of Technology (TNUT), the course "Electrical Materials and Electrical Apparatus" plays a pivotal role within the undergraduate curriculum, serving as a foundation for students' technical competence. By incorporating advanced developments in the field of nanodielectrics, the faculty can transition its pedagogical approach from a largely traditional and phenomenological framework to one that is more research-driven and application-oriented. This shift might include the utilization of real-world case studies, such as the application of epoxy nanocomposites in gas-insulated switchgear (GIS) spacers and high-voltage direct current (HVDC) cables. Additionally, laboratory-based modules could provide practical exposure to nanofiller dispersion techniques, dielectric spectroscopy, and partial discharge measurement, employing cost-effective bench-top equipment to ensure accessibility. For postgraduate students, the department offers avenues to undertake thesis projects focusing on the exploration of locally sourced raw materials, such as silica and boron nitride derived from Vietnam. These projects could assess the performance of these materials under aging tests conducted in tropical environmental conditions, with potential implications for improving material resilience and functionality. These initiatives align well with Vietnam's national priorities in energy security and sustainable development, providing a framework for knowledge generation that directly addresses domestic challenges. Updating the curriculum to meet the demands of emerging sectors such as electric vehicle (EV) charging infrastructure, renewable energy substation design, and smart grid maintenance is essential for equipping graduates with relevant expertise. To this end, specialized modules could be introduced in areas including interfacial engineering of insulators, Weibull statistical analysis for reliability assessment, and artificial intelligence-based material design. Additionally, fostering collaborations with industry stakeholders like Vietnam Electricity (EVN) and local manufacturers could bridge gaps between academic training and practical industry requirements. Partnerships with globally recognized research organizations, such as the IEEE Dielectrics and Electrical Insulation Society (DEIS), would further enhance TNUT's international academic standing. By embedding cutting-edge knowledge of nanodielectrics into its programs, TNUT can prepare engineers who specialize in the specification, testing, and maintenance of advanced insulation systems, contributing to Vietnam's progression toward a more sustainable and efficient power generation and distribution network.

## III. Conclusion

Between 2023 and 2026, epoxy-based nanodielectrics have demonstrated significant progress, evolving from experimental materials towards commercial viability. These advancements have led to marked improvements in properties such as dielectric strength, thermal stability, and mechanical durability—attributes critical to the design of compact, reliable, and environmentally sustainable high-voltage equipment. However, key challenges remain unresolved, including issues of large-scale manufacturing, long-term material endurance, standardization protocols, and ecological sustainability. Future research avenues focusing on AI-guided material development, the advancement of self-healing polymers, and the creation of bio-derived formulations hold promise for addressing these limitations over the next decade. For TNUT’s Faculty of Electrical Engineering, these advancements offer an invaluable opportunity to enhance instructional methodologies, upgrade laboratory facilities, and cultivate a new generation of professionals skilled in advanced insulation technologies. By maintaining strategic investments in both fundamental research and applied developments within nanodielectric materials, Vietnam can significantly contribute toward global efforts in transitioning to intelligent, decarbonized electricity systems while bolstering its own energy independence and economic sustainability.

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