SVU-International Journal of Engineering Sciences and Applications (2024) 5(2): 153-161
Print ISSN 2785-9967 | Online 2735-4571
DOI 10.21608/SVUSRC.2024.284150.1216

Recent Advances in Strengthening Electrical, Mechanical and Thermal Properties of Epoxy-Based Insulators for Electrical Applications

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Abstract Epoxy resin is widely used as an insulation material in various applications, including transformers, GIS switch gears, and electronics. Employing micro-nano-sized fillers inside epoxy-based composites has been shown to enhance their thermal, mechanical, and electrical properties. The type and concentration of filler are important factors in advancing the performance of epoxy resins as insulation materials for various industrial applications. This study explored the resulting enhancement in mechanical and electrical characteristics, particularly dielectric strength and flashover, in epoxy-based composites due to the incorporation of micro-nano-sized fillers. Additionally, this work experimentally examined the effectiveness of incorporating nanofiller into epoxy-based composites on their dielectric strength.

Keywords: Epoxy; Insulators; Electrical Properties; Dielectric Strength; Fillers; Micro composites; Nano composites.

1 Introduction

In recent times, epoxy resin materials have demonstrated commendable insulation properties across various electrical applications, particularly proving to be ideal for components in transformers, switchgear, generators, and drives [1]. In some applications, such as the insulation systems of large electrical machines, mechanical strength and thermal conductivity are equally important as electrical properties.

Permittivity and dissipation factors should be as low as possible for electrical insulation. Additionally, flame retardancy is a desired quality for cable insulation used in tunnel fields [2].

Epoxy-based nanocomposites play a crucial role in safeguarding electrical components against environmental factors such as moisture, atmospheric gases, current leakage, and solvents, while also effectively mitigating mechanical impacts like shocks, heat, and vibrations [3-6].

The advantages of epoxy over alternative solutions are manifold, owing to its renowned adaptability and resilience. This has led to lighter, smaller, and more flexible insulators, instruments, and dry-type distribution transformers. Epoxy resins offer excellent insulation between closely packed electrical parts and exhibit high adherence to substrates, making them suitable for contemporary applications like microelectronics packaging [5].

While epoxy resins possess excellent electrical and chemical properties such as voltage endurance, adhesive strength, wear resistance, and water repellency [7, 8] they fall short in serving as solid insulating materials for ultra-high voltage (UHV) power equipment due to inadequate mechanical and thermal attributes. Moreover, the exothermic reaction occurring during the curing process alters the reaction rate, impacting the cross-linking mechanism and inducing internal cavities and surface deformations [9, 10].

To address these deficiencies, research is underway on epoxy nano-micro composites to enhance tensile strength, compression, coefficient of thermal expansion, and glass transition temperature through methods such as polymerization, rubber dispersion, or incorporation of inorganic nano-micro fillers [11-13].

Epoxy composites represent progress in advancing

Received: 21 April 2024 / Accepted: 16 May 2024

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both the; physical and chemical performances of pure epoxy. The primary objective of utilizing epoxy composites as insulating materials is to capitalize on the benefits of epoxy while mitigating drawbacks, primarily through the corporation of inorganic fillers [9].

2 Dielectric Materials

The use of insulating materials restricts the flow of electricity. Materials with low conductivity and high resistivity, such as the plastic used for plugs and the insulating oil used in transformers, are accessible in solid, liquid, and gaseous forms thanks to the formation of ionic bonding [14].

A summary of insulating materials used in electrical networks is shown in **Fig.** 1.

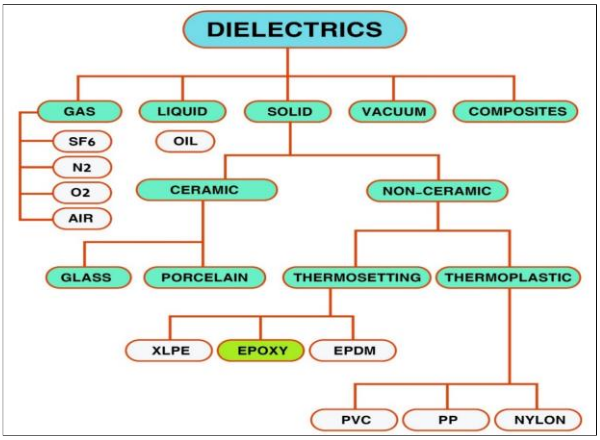

Fig. 1 Classification of insulating materials.

Due to the extraordinarily high resistance of insulators, supplying a few milliamperes of current through them requires an extremely high voltage, such as kilo or megavolts. In order to insulate the conductor from the ground, insulators are utilized in every household and piece of commercial electrical equipment.

In addition, due to the negative temperature coefficient of resistance of polymeric insulating materials [15], resistivity decreases as temperature rises. Since no electrical equipment can operate without an insulator, the failure of insulation is the primary cause of most failures in the field of electrical engineering.

Because there are so many kinds of insulators on the market, the importance of insulating materials is growing every day. Also, because the type of material used affects the equipment's lifespan, choosing the appropriate insulating material is crucial.

3 Polymer Composites and Fillers

The composite insulator is another name for the polymer or polymeric insulator [16]. It has good mechanical strength and is a lightweight insulating material [17]. The polymer insulator's drawback is that moisture can enter if there is an unwelcome gap between the weather shed and the core.

Composite materials are commonly preferred over traditional materials due to their improved material performance, which includes high strength, toughness, heat resistance, light weight, impermeability against gases, thermal endurance and stability in the presence of aggressive chemicals, water, and hydrocarbons, high resistance to fatigue and corrosion degradation, re-processing recyclability, and less leakage of small molecules such as stabilizers, and so on [1,2]. **Fig.** 2 depicts different types of inorganic fillers.

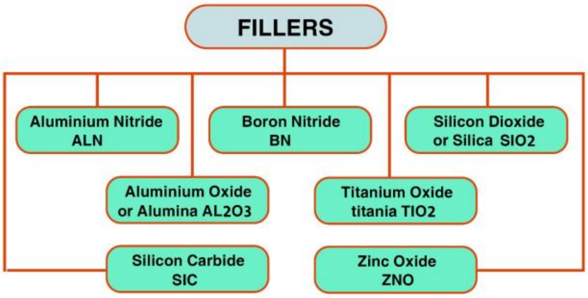

Fig. 2 Types of inorganic fillers.

In the power industry, inorganic fillers (such as Aluminum Nitride (ALN), Boron Nitride (BN), Silicon Dioxide or Silica (SiO_2), Aluminum Oxide or Alumina (Al_2O_3), Titanium Oxide or Titania (TiO_2), Silicon Carbide (SiC), and Zinc Oxide (ZnO), among others) are commonly incorporated into electrical insulating polymers to achieve specific electrical, mechanical, and thermal properties [18-22].

4 Literature Review for Recent Progress in Epoxy-Based Nan-Micro composites

In [23], researchers have focused on enhancing the dielectric properties of epoxy nanocomposites. In their investigation, they explored the incorporation of Silica and Graphene Oxide (GO) nano-fillers into epoxy resin, to improve its suitability for high voltage insulation applications. Their findings revealed that the addition of Silica nanofillers led to improvements in the dielectric strength of the Silica-epoxy resin composite. Particularly, a smaller percentage of Silica nano-fillers showed promising results, with the maximum breakdown voltage observed at a composition of 2% (w/w) silicon oxide particles. However, it was noted that increasing the concentration of Silica nano-fillers beyond 5% (w/w) resulted in a drastic reduction in dielectric breakdown strength. Contrastingly, the incorporation of Graphene Oxide (GO) nanofillers was found to decrease the breakdown strength of the nanocomposite samples. Consequently, it was concluded that GO nanofillers are not suitable for enhancing the dielectric strength of epoxy composites. Moreover, the study observed that the relative permittivity was higher at lower nano-filler concentrations, specifically within the range of 2% to 4% (w/w), for both Silica and GO nano-fillers. Thus, it was demonstrated that, in terms of dielectric strength and relative permittivity, the optimal enhancement was achieved with Silicon Oxide nano-fillers at concentrations of 2% to 3% (w/w) in the epoxy resin. Furthermore, simulation results indicated that the electric field and potential distribution calculations, based on the tested parameter values, remained within acceptable limits. This suggests that the improved dielectric properties achieved through the incorporation of Silica nano-fillers could enhance the performance of epoxy insulation in high voltage applications.

The research [24] focused on investigating the impact of interface structure variations of Al_2O_3 nanoparticles on the dielectric properties of epoxy nanocomposites. Three different interface structures were examined: surface untreated Al_2O_3, Al_2O_3-APS, and Al_2O_3-HBP nanoparticles. The study yielded significant findings that underscored the influence of these different interface structures on the dielectric properties of the epoxy nanocomposites. A notable outcome of the study was the discernible effect of the adopted nanocomposites, which highlighted the importance of the interface structure of Al_2O_3 nanoparticles in shaping the dielectric properties of epoxy nanocomposites. The researchers concluded that, across all types of epoxy nanocomposites, the effective dielectric constant exhibited an increase with higher nanoparticle loading.

In [25], the researchers in their study examined the environmental impact on the flashover voltage of epoxy composite materials. They observed that epoxy composites incorporating ATH filler demonstrated higher flashover voltage values compared to those without ATH filler across various environmental conditions. Notably, ATH filler exhibited the highest flashover voltage, reaching 42.41 kV for a 30mm length under dry conditions, while registering the lowest value of 9.67 kV for a 10mm length under conditions of 54000μS/Cm salinity concentration. The researchers found that environmental conditions played a significant role in the variation of flashover voltage values, with dry conditions yielding the highest values and conditions of 54000μS/Cm salinity concentration resulting in the lowest values for the same length and filler type. Moreover, they concluded that ATH filler was the most effective filler type for maximizing flashover voltage in epoxy composites across all lengths and conditions due to its ability to fill pores, resulting in a smoother surface and decreased surface leakage current. Additionally, the study revealed that pure epoxy composites generally exhibited lower flashover voltage values compared to composites containing other filler types across all lengths and conditions.

The researchers in [26], conducted a thorough examination of the electrical, thermal, and mechanical attributes of epoxy resin employed in molded transformers for large-scale electric utilities domestically. Employing a nanocomposite framework, they scrutinized AC insulation breakdown strength, thermal conductivity, and linear thermal expansion coefficient of epoxy composite materials formulated with varying proportions (5-15 phr) of nanofillers such as MgO, CuO, C, Ag, and ZnO blended with basic epoxy resin. Their investigation uncovered significant insights: enhancements in thermal conductivity facilitated improved heat conduction from winding wires and transformer cores, resulting in reduced internal temperature rise within insulating materials. Notably, the addition of nano-ZnO substantially elevated thermal conductivity by approximately 1.09 W/m·K, signifying a 20% improvement over the base value for epoxy resin. Furthermore, addressing the substantial difference in thermal expansion coefficients between epoxy resin and transformer conductors, the study demonstrated that incorporating MgO at 15 phr significantly reduced the thermal expansion coefficient to approximately 35 ppm/K. AC insulation breakdown tests indicated strengthened values ranging from 17-31 kV/mm, with epoxy composite materials containing MgO, Ag, and ZnO showing pronounced improvements, especially at elevated temperatures. The study's overarching objective was to enhance the electrical, thermal, and mechanical properties of insulating resins for molded transformers, achieving key milestones such as the identification of micro epoxy composites with enhanced AC insulation breakdown properties and the development of nano-micro epoxy composites offering improved thermal and mechanical characteristics. Subsequent research should explore a broader range of nanofillers and delve into the size and concentration of mineral particles to foster further advancements in transformer technology.

In [27], researchers detailed their study on epoxy-clay nanocomposites, which were fabricated using two organo-modified MMTs. They noted that the nanocomposites exhibited a higher elastic modulus compared to the pure epoxy matrix, attributed to the substantially greater stiffness of the clay and the limitation of polymer chain mobility caused by the presence of clay particles. Additionally, they observed an increased breakdown strength across all nanocomposites, contrasting with the epoxy's breakdown strength of 11.7 kV mm^{-1}. Values for the nanocomposites ranged from 13.0 to 14.7 kV mm^{-1}. This enhancement was credited to the nanocomposites' heightened resistance to surface degradation caused by partial discharges, thereby impeding the propagation of electrical trees. Despite the electrical tree's attraction to clay particles due to their higher permittivity, the nanocomposites superior degradation resistance ultimately countered this effect.

In [28] researchers concluded that epoxy-based nanocomposites hold significant promise for use in high voltage insulation materials. They noted that the incorporation of inorganic oxide nanoparticles not only provides mechanical reinforcement, as traditionally achieved with micrometer-sized particles, but also enhances the dielectric breakdown strength while reducing dielectric loss and relative permittivity of the material.

Researchers in [29], concluded their study by investigating the thermal and electrical properties of two types of micro composites: alumina and silica micro composites, reinforced with nanosized fillers. Their findings revealed that the inclusion of small quantities of nanosized fillers (less than 1 vol %) resulted in improvements in both thermal and electrical performance of epoxy-based micro composites. Notably, the addition of 0.6 vol % of nanosized hexagonal boron nitride to silica micro composite led to a 30% increase in thermal conductivity, a 65% enhancement in AC breakdown strength, and a 50% improvement in DC breakdown strength.

In [30], researchers concluded that the electrical properties of epoxy composites filled with silica nanoparticles at a concentration of 0.1% exhibit reliability and surpass those of micro silica composites at the same concentration. The incorporation of silica nano filler in the composite resulted in a maximum dielectric strength of 103 kV/mm, compared to the epoxy's maximum dielectric strength of 84 kV/mm. Hybrid composites containing micro titanium dioxide and micro silica achieved a dielectric strength of 97.35 kV/mm, whereas micro composites with silica and titanium dioxide fillers individually recorded 95.2 kV/mm and 91.8 kV/mm, respectively. Additionally, hybrid composites filled with both micro and nano silica fillers demonstrated a dielectric strength of 94 kV/mm. Overall, the inclusion of nano silica filler significantly enhanced the electrical properties of epoxy composites and led to an increase in their dielectric strength.

5 Potential Applications of Epoxy-based Nanocomposites

5.1 Epoxy Resin Dry-Type Transformers

A dry-type transformer is frequently better suited for a given application than a liquid-filled transformer [31, 32]. The technology of medium-voltage dry-type transformers has advanced quickly due to improvements in solid insulating materials over the past few decades [33]. These novel materials enable the transformers to demonstrate exceptional resistance to the effects of humidity, surge voltages, and short-circuit currents.

Compared to earlier designs, new dry-type transformers have lower noise levels and can tolerate high temperatures, which leads to very compact designs. As a result, they are lighter than comparable oil transformers, which lowers the cost of installation and cranes. Additionally, these transformers are environmentally friendly and have a low flammability hazard [34].

There are several medium-voltage applications, including power distribution, drive/rectifiers, heavy-duty traction, and offshore wind farms, that can use a variety of indoor and outdoor transformer designs [35-37].

Transformers must be protected against fire and explosion in specific situations, such as homes and hospitals. As a result, experts and designers favor novel transformer types and, as a result, non-flammable transformers [32].

Glass fiber-reinforced epoxy resin, as a significant insulation material in dry-type transformers, has survived the heat within the transformer for a long period, and its effectiveness as an insulation material directly impacts the operating performance of dry-type transformers [38]. These transformers are built with non-flammable insulation.

Askarel is one of these insulations that contains polychlorinated biphenyls (PCBs). However, it was decided that PCBs were not ecologically safe in the middle of the 1970s. As a result, askarel use in existing transformers has been gradually phased out [39,40].

As a result, many types of new transformers have been created, with dry-type transformers being a popular variety.

Cast-resin dry-type transformers are one of the most popular types. These transformers provide flammability and moisture-attraction protection [41].

5.2 Epoxy Resin in Switchgears

Switchgear is a crucial component of the reliable power supply that supports social infrastructure. Many years have passed since the introduction of open-type switchgear in the 1890s [42].

According to the needs of the time, switchgear design has evolved from open to housed to metal-enclosed to sealed. The size, capacity, durability, environmentally friendly nature, reliability, and maintenance requirements of the devices have all increased. The advancement of insulating methods has a significant impact on the design and development of switchgear. In switchgear, the standard insulation methods have changed from air insulation to air-based composite insulation (barrier insulation, cladding insulation), and then to SF_6 gas insulation. The devices are now more compact and offer better insulation performance.

In the medium-voltage range of 24 to 84 kV, cubicle-type gas-insulated switchgear (C-GIS) with low-pressure SF6 gas enclosed in a rectangular container is frequently employed at the moment [42].

In power switching equipment, SF_6 is frequently employed as an insulating and arc extinguishing medium since it is a nontoxic, odorless, inert, nonflammable gas with outstanding dielectric strength and capacity.

SF_6 was recognized as a greenhouse gas by the 1997 Conference of the Parties on Climate Change (COP3) because it has a global warming potential (GWP) 23,900 times greater than that of CO_2 [43]. Since then, there has been a lot of work done on finding alternatives to SF_6 gas, leading to switchgear that uses high-pressure air and nitrogen [44-47].

Furthermore, research has been conducted on extra-high voltage class next-generation switches and transformers with solid insulation [48].

Additionally, solid insulators were discovered that provided superior insulating performance compared to low-pressure SF_6 gas, with the goal of producing SF_6-free switchgear by molding the primary circuits, including vacuum bottles, with epoxy resin [42].

Epoxy resin is an indispensable material for insulation systems of solid-insulated switchgear (SIS) and gas-insulated switchgear (GIS). Numerous epoxy castings are needed in SIS to shape primary circuits, while in GIS, specialized insulated spacers are needed to support the interior conductor [49,50].

5.3 Epoxy Resin in Turbine-Driven Generators

The design trend for turbine-driven generators over the last few decades has been toward ever-increasing power from the same or even smaller units. This tendency has been influenced by several innovations and design adjustments. Two key developments—the adoption of conductor cooling and the creation of new insulation systems have each played a significant role in this continuous transition for big-size (>240,000 kVA) turbine-generators.

However, applying conductor cooling to the armature winding has not been shown to be cost-effective for medium-sized turbine-generator systems (<240,000 kVA). As a result, improvements to the insulation system and the determination of the maximum permissible operating conditions for long-term reliable operation have largely influenced design revisions for the armatures of medium-size turbine-generators. The enhanced properties of an insulating system for higher temperatures offer benefits for many applications where increased capacity and/or a smaller machine size are crucial [51].

For instance, it is occasionally desirable to rewind an old generator for a greater voltage rating than what the device was intended for. When using the current insulating technologies, this is typically not possible without considerable output loss. But while operating at a greater temperature, the rated voltage may be raised while the rated output remains the same. Similar to this, it is occasionally desirable to boost a machine's output while keeping its rated working voltage. Higher operating temperatures will again be the answer to this. The operating temperature of the field windings often doesn't need to alter significantly when the desired new rating is at an increased power factor. Additionally, for transportable applications, the capacity to operate at a higher temperature under intense cyclic loads with a smaller machine and less weight is crucial.

A new generator armature insulation system that can operate at higher temperatures (155 °C) is desirable as a result of the abovementioned particular uses. Any new insulating system for high-voltage turbine generator units must provide safe and dependable long-term performance under the mechanical and electrical conditions present during generator operations. This demands an insulation system with exceptional voltage endurance, strong insulation resistance, resistance to internal and external electrical discharges (corona), and sufficient mechanical strength to withstand tape separation ("girth cracking"), generator vibration, and short circuit stresses.

A novel composite epoxy resin-bonded mica paper insulation system has been created after a lengthy development effort to satisfy the specifications outlined [51].

5.4 Epoxy Resin in Electronic Devices

Epoxy resins are frequently used to coat and encase electrical circuit components and electronic by isolating the device from harmful environmental effects like atmospheric gases, moisture, current leakage, solvents, microorganisms, mechanical shock, and vibrations, epoxy resins protect electronic devices from these effects. They offer the necessary insulation between tightly packed, delicate electrical elements in a more contemporary use known as micro-electronics packaging, with excellent adhesion to both the substrate and the elements [52].

6 Martials and Methods

Materials used in this paper is summarized in **table 1.**

Table 1 Components of examined materials

Material	Description
Thermoset Epoxy Resin	100 parts by weight. Viscosity: 400 mPa.s at 25°C. Density: 1.15 g/cm^3 at 25°C.
Epoxy hardener	45 parts by weight. Viscosity: 400 mPa.s at 25°C. Density: 1.0 g/cm^3 at 25°C.
Titanium Dioxide	Preparation method: Sol Jel. Scale: Nano sized. Particle Size: 30 ± 5 nm

7 Thermoset Epoxy Composites Preparation

Seven samples will be prepared for the experiment. Initially, a pure neat thermoset epoxy (TS-EP) sample is created by combining 100 parts by weight of TS-EP with 45 parts by weight of hardener. This mixture is then stirred for 3 minutes using a magnetic stirrer and subsequently vacuum degassed to remove any bubbles. The resulting mixture is poured into dishes with a diameter of 5cm and a thickness of 2mm. The samples are then left to cure at room temperature for a period of 15 days before being released for testing.

For the remaining six samples, nano TiO_2 filler is incorporated into the pure thermoset TS-EP at concentrations ranging from 0.5% to 3% of the total weight. The mixture undergoes sonication to ensure good dispersion of the filler [53, 54]. Hardener is gradually added to the mixture and manually mixed for 10 minutes. Finally, the samples are vacuum degassed, poured into dishes of the same dimensions, and left to cure at room temperature for 15 days before testing begins.

8 Results and Discussion

Testing the samples under dry conditions involved the application of AC voltage according to ASTM D149 [55]. Subsequently, the dielectric strength of each sample was determined: the pure TS-EP exhibited a dielectric strength of 26.768 kV/mm, while the sample containing 0.5% TiO_2 filler displayed a dielectric strength of 27.233 kV/mm. As the TiO_2 filler concentration increased, the mean dielectric strength also rose: 27.651 kV/mm for 1% TiO_2 filler, 28.027 kV/mm for 1.5% TiO_2 filler, 28.366 kV/mm for 2% TiO_2 filler, 28.673 kV/mm for 2.5% TiO_2 filler and 28.951 kV/mm for 3% TiO_2 filler. The inclusion of nano TiO_2 filler in samples 0.5% through 3% TiO_2 filler led to incremental enhancement in dielectric strength, ranging from 1.74% to 8.16%.

Fig. 3 depicts the relationship between Dielectric strength in kV/mm and the percentage of enhancement resulting from the inclusion of TiO_2 nano filler inside the TS-EP samples. The x-axis represents the percentage of TiO_2 filler added to the TS-EP, ranging from 0.5% to 3%, while two y-axes represent distinct parameters, the primary y-axis illustrates Dielectric strength in kV/mm, while the secondary y-axis depicts the percentage of enhancement. The graph showcases a clear upward trend, indicating that as the concentration of TiO_2 filler increases, there is a corresponding enhancement in Dielectric strength. This enhancement is quantified by the percentage increase, which is prominently displayed on the graph. The graph provides a visual representation of how the addition of nano TiO_2 filler positively impacts the dielectric strength of the epoxy composite samples.

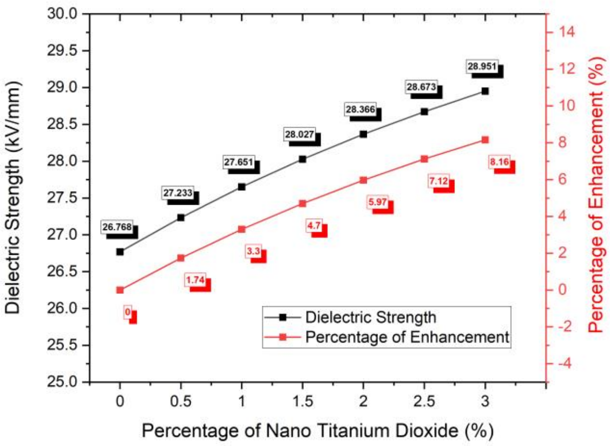

Fig. 3 Dielectric strength and percentage of enhancement of nano TiO_2 composite.

9 Conclusion

In conclusion, this study delved into the progress of nano- and micro-composites in enhancing the electrical, mechanical and thermal characteristics of epoxy insulation systems. Epoxy-based insulators are widely adopted in various industrial applications, including transformers, GIS switchgears, and electronics. Through a comprehensive review of existing research, it is evident that; the incorporation of nanosized fillers, such as titanium dioxide, silica and hexagonal boron nitride, holds promise for improving dielectric strength. Additionally, investigations into micro composites reinforced with materials like alumina and silica showcase advancements in thermal and electrical properties.

Moreover, the discussion on epoxy resin applications in dry-type transformers, switchgears, turbine-driven generators, and electronic devices emphasizes the significance of continuous innovation in insulation technology. The transition towards non-flammable and environmentally friendly insulation materials, such as epoxy resin, is essential for ensuring the safety, reliability, and sustainability of electrical systems.

This study presented a foundation for future research endeavors in the epoxy insulation area. The literature review highlights the significance of understanding filler type, concentration, and epoxy matrix interaction in optimizing insulation materials for enhanced performance. Further empirical studies are warranted to validate the potential benefits of nano and micro composites in epoxy insulation systems.

In essence, this study underscores the importance of continual exploration and innovation in insulation technology to meet the evolving demands of modern electrical systems. By leveraging the capabilities of nano- and micro-composites, the potential exists to develop more efficient, reliable, and sustainable insulation solutions for a wide range of industrial applications.

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