


# Advancing High-Voltage Polymeric Insulators: A Comprehensive Review on the Impact of Nanotechnology on Material Properties

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**Abstract** This study focused on the performance of polymeric materials, which have garnered significant interest across various industries. The initial generation of polymeric insulators utilized materials like epoxy, silicone rubber, and ethylene propylene diene monomer for shed applications. Among these, silicone rubber emerged as the most promising material, as demonstrated through global experience. Researchers worldwide are exploring the use of micro, nano, and hybrid micro/nano inorganic fillers in base polymers to improve insulator durability and cost-effectiveness. The study focuses on the influence of fillers on thermal, electrical, and mechanical properties, as well as their resistance to corona discharge tracking and erosion. This paper highlights key advancements in polymer nanocomposites while identifying potential areas for future exploration within the realm of high-voltage electrical insulation. The use of various inorganic fillers has demonstrated significant potential in enhancing aging resistance, thereby strengthening the use of polymeric materials in advanced insulation applications for modern power systems.

**Keywords:** Polymeric Insulators; Micro/Nano Inorganic Fillers; Electrical properties; Mechanical properties; Thermal properties.

## 1 Introduction

In overhead transmission systems, insulators act as a

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vital barrier between each phase and the grounded crossarm, keeping current from leaking to the earth and supporting line conductors. As a result, insulators require excellent mechanical strength to weight ratios, high electrical insulation resistance, high thermal conductivity, ease of molding, and reduced maintenance costs [1, 2]. In order to choose insulators, one must ensure long-term performance and cost considerations, which vary depending on the nature of the responsibilities [3, 4]. As power systems adapt to growing demands and incorporate renewable energy sources [5-16], the role of insulators becomes increasingly crucial [17-22].

Glass and porcelain insulators have historically been used extensively for outdoor high-voltage insulation, and their necessary material qualities have long been understood [23]. Several decades of in-service experience demonstrate that these materials are both reasonably priced and have exceptional resistance to electrical and environmental stress, but also economically priced [24]. On the other hand, these materials provide problems and challenges from the standpoint of a utility because of their bulkiness, which makes installation and maintenance labor-intensive and their poor performance in severely polluted locations.

When polymeric insulators first appeared in 1960 [25], electric utilities and equipment manufacturers regarded them as a potentially attractive replacement for ceramics.

Due to its chemical structure, a polymeric material simplifies the design and production of complex designs. A polymeric insulator has several notable benefits, such as being lightweight [26, 27], having a compact line design, and providing protection against successive failures. The polymeric insulator surface's hydrophobicity is also kept even when it's wet, as shown by its low surface energy [28-30].

Mohammed Amin and Mohammed Salman discussed the development of polymer insulators, their historical development, ageing, and the relationship between pollution levels and creepage distance. They concluded

that polymeric insulators offer benefits like contamination performance, lower construction costs, lightweight design, low maintenance, vandalism resistance, and compact design. The choice of material and insulator architecture and design significantly impact their performance in electric power substations and distribution and transmission lines [31-33].

Silicone rubber (SiR) is often used as a shed material because it has a high-volume resistivity, a very high breakdown strength, and the ability to get its surface hydrophobicity back in tough conditions. However, it is more costly, has a weaker mechanical construction, and is less tracking-resistant [34-36]. Conversely, EPDM is comparatively stronger mechanically and shows superior resistance to tracking and erosion. In contrast to SiR, it has lower volume and surface resistivity [37-39]. In terms of overall performance, it has been reported that SiR-based polymeric insulators have comparatively better standing [40-42].

Polymeric insulators, like SiR, EPDM, and epoxy, age due to exposure to the outdoor environment, causing partial degradation of their dielectric, thermal, and mechanical properties [43-45]. Electrical stresses and environmental stresses weakly affect polymeric sheds, causing degradation and surface tracking, which in turn leads to puncturing and surface erosion [46, 47]. Environmental stresses like acid rain, UV radiation, and moisture cause the ageing of polymeric insulators [44, 48, 49]. These stresses can cause thermal impact, corrosion, and leakage current flow, leading to flashovers and permanent failure. Researchers are now modifying these materials with micro- and nanofillers.

This work reviews polymers loaded with inorganic materials and their performance in the context of second-generation polymeric insulators. It reviews global studies on composites with the potential for manufacturing these insulators. The review also covers how inorganic fillers affect age-retarding phenomena such as hydrophobicity recovery performance and corona-caused aging.

## 2 Polymeric materials used as insulators

A polymer can be defined as a long-chain molecule that is composed of many repeating units of identical structure. There are both naturally occurring and synthetic polymers. Polymers are formed by chemical reactions in which many molecules called monomers are joined sequentially, forming a chain. In many polymers, only one monomer is used. In others, two or three different monomers may be

combined [50].

Several publications argue that extruded polymer insulation is likely to represent an increasing share of the market. It represents about 70% of all the installed new high voltage insulators, and their shares of the market continue to grow due to its advantages, which include a higher operating temperature, affordable manufacturing, lightweight design, and lower maintenance costs [51-53].

Since the early 20th century, polymers have been extensively employed as electrically insulating materials. Heat, humidity, salinity, and mechanical stress are some of the aging factors that can alter the dielectric characteristics of insulation polymers over time [52].

Polymeric materials are popular due to their lightweight, simple structure, high mechanical strength, pollution-resistant performance, and ease of transportation. However, they also have disadvantages like chemical changes, exposure to arcing or flash, and difficulty in tracing potential failures. A variety of polymeric insulating materials has been developed, each with unique characteristics [53, 54].

## 3 Type of Polymer

### 3.1 Thermoplastic Polymers

Linear or branching polymers known as thermoplastics may flow and soften when heated, form complex structures when chilled, and solidify when cooled [55]. Although the number of cycles may be limited by chemical deterioration, they may be remolded several times without experiencing any consequences on their chemical structure. Thermoplastics have the benefit of recyclable waste and the ability to re-ground and re-mold damaged or rejected parts [56]. Polystyrene, polyethylene, polypropylene, and poly(vinyl chloride) are the greatest volume thermoplastics. Polyamide (nylon), polycarbonate, and polyethylene terephthalate are further thermoplastics. Because of their insulating qualities, plastics are employed in a variety of products.

### 3.2 Thermosetting Polymers

Thermosets are stiff and brittle polymers with a cross-linked network structure, making them resistance to chemicals and solvents [57, 58]. When heated, they do not melt because of the cross-link, which stops chains from slipping past one another. Thermoset material softens when heated, but further heating can cause decomposition. Thermosets are formed by pouring them into a mold, in

contrast to thermoplastics, which starts a chemical process known as curing that forms cross-links and hardens the material, giving it a permanent shape. Thermosets are a type of thermoplastic used in insulation, particularly for electric wiring and switches, circuit breakers, light fittings, and handles. They are made by mixing ingredients like polymer, colorants, curing agents, fillers, and other additives, then heated and cooled [59, 60].

### 3.3 Elastomers

Polymers known as elastomers can stretch several times their initial length and rapidly regain their original form when stress is removed. Their name comes from the Greek words "elastic," meaning a material's ability to return to its original shape, and "mer," meaning part. They are named after the words "elastic" and "mer" and are used in high voltage (HV) insulators because they may regain their natural shape without suffering permanent deformation. Thermoplastic elastomer (TPE) is the third generation of HV insulating polymeric materials, specifically designed for distribution class applications in environments prone to light contamination. Elastomers are popular for their performance and lower cost, making them a popular choice for insulators [61-63].

### 4 Type of Filler

The new polymer composites are gaining attention because of their enhanced mechanical, thermal, and electrical characteristics compared to traditional polymers. These composite materials offer superior performance, including stability, toughness, heat resistance, low weight, thermal endurance, fatigue resistance, corrosion degradation, reprocess ability, and less small molecule leakage [64-66]. Various kinds of inorganic fillers are shown in Fig. 1.

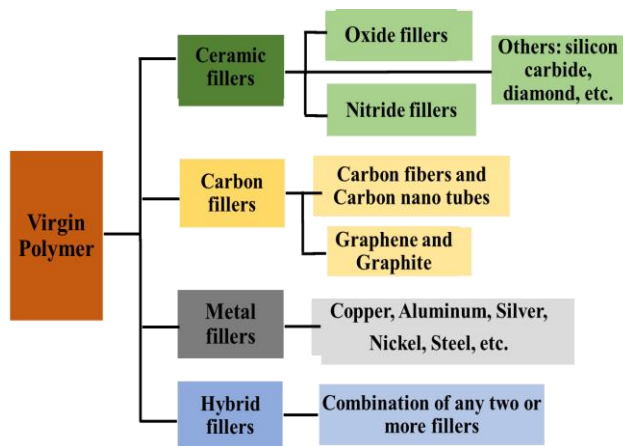


Fig. 1 Types of filler.

### 5 Composite Polymer and Fillers

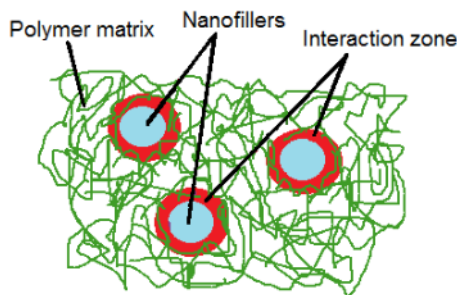
A composite is a material system consisting of two or more distinct constituents, each with different physical identities and functions. The base material is typically a polymer, while the other components include additives or fillers [67, 68]. In electrical insulation systems, fillers are used instead of additives. Synthetic inorganic fillers, such as oxides, nitrides, and carbides, are commonly used in high-voltage insulation systems to improve polymeric materials' characteristics. Silicon dioxide, titanium oxide, aluminum oxide, zinc oxide, magnesium oxide, and silicon carbide are a few examples of these fillers. This filler enhances the performance of the composite system [69, 70].

To prevent cluster formation and improve the adherence of the polymer and filler, polymeric insulators with different fillers require homogenous dispersion. This may be done by altering the filler's surface inside the polymeric matrix [71, 72]. Compatibility is improved via improved dispersion, which is important at the contact between the filler and the polymeric basis material [73].

A silane coupling agent is used to change the surface of a filler. It goes through chemical reactions like hydrolysis and mixing with a polymeric base material. The silane attaches itself to the filler surface after being formed from the alkoxy group of silanes. The polymeric substance interacts with the coupling agent's organic groups that are affixed to the filler's surface. After the final preparation and curing, a scanning electron microscope is used to check how the filler is dispersed. This shows that changing the surface makes it less likely for particles to stick together, which leads to better dispersion [74, 75].

The three primary parts of polymer nanocomposites are the interaction zone, the nanofiller, and the polymer matrix. A simplified schematic showing the components of polymer nanocomposites is shown in Fig. 2.

The interaction zone is crucial for improving the properties of these nanocomposites. The polymer matrix can be categorized as elastomers, thermosetting, and thermoplastics. Nanofillers can be one-dimensional, two-dimensional, or three-dimensional. Three-dimensional minerals like silica (SiO<sub>2</sub>), alumina (Al<sub>2</sub>O<sub>3</sub>), and titania (TiO<sub>2</sub>), as well as one-dimensional materials such as layered silicates or clays, are pertinent nanofillers for insulation.



**Fig. 2** Simplified diagram illustrating constituents' polymer nanocomposites.

## 6 Role of Fillers on Important Properties of Polymeric Insulators

### 6.1 Enhancement of Electrical Properties

This section presents the electrical work that has been done by various researchers to examine the electrical properties of insulating materials, such as dielectric strength, dry band arcing phenomena, and flashover events resulting in random surface discharges. Additionally, the impact of fillers in enhancing the electrical characteristics has been discussed in detail. These discharges have the potential to damage the surface hydrophobicity, thereby consuming the thin polymeric layer, and increase the intensity of the electric field, which in turn leads to an increase in surface electrical discharges. Water molecules, which have higher conductivity than polymeric materials, decrease flashover voltage due to increased polarization and dielectric loss [40, 76]. When pores or voids are present in bulk polymeric insulators, they can cause partial discharge and lower dielectric strength because charges can build up [77]. This leads to surface degradation and ultimately complete failure. Inorganic fillers can be added to a base polymer to change its dielectric strength; this usually results in better performance at low filler loading. Factors such as filler type, shape, size, dispersion, and matrix properties can affect this. However, dielectric strength may drop over a specific concentration known as the dielectric percolation threshold [78].

The transition behavior of a composite dielectric with a higher filler content is referred to as the percolation threshold. The highest dielectric strength value is dictated by the contact between the polymer and filler.

For instance, nano silica/epoxy composites have a percolation threshold of 5 wt% silica, while carbon black-

filled composites have a threshold of 6.2 wt% [79, 80]. The addition of filler enhances dielectric strength due to shallow traps that retard space charge accumulation. The addition of filler enhances dielectric strength due to shallow traps that retard space charge accumulation. However, once the filler content reaches a certain level, the easy overlapping of charge carriers in a double layer led to the formation of percolation paths, thereby decreasing the dielectric strength. As the amount of filler goes up, the distance between particles equals the diameter of the filler particles. This makes it easy for charge carriers to overlap, which makes the dielectric strength go down.

Frechette et al. used a two-dimensional computer-generated composite model to describe the epoxy's interphase and overlap regions. They found that interphase particle overlap significantly influences the composite's dielectric response. The dielectric strength of epoxy resin under AC voltage was greatly enhanced by the addition of less than 1 weight percent nanosized ZnO. They conducted experimental studies on epoxy/polyhedral oligomeric silsesquioxanes (POSS) to improve dielectric strength and thermal conductivity behavior [81].

Andritsch et al. found that epoxy filled with nano BN increased its dielectric strength due to surface modification of the polymer nanocomposite [82]. This was due to better suppression of mobile charge carriers at the interface region between the polymer matrix and filler. A smaller filler size may enhance dielectric performance, as it allows better penetration of charge carriers through the composite's bulk. HTV-SiR filled with 6 wt% nano SiO<sub>2</sub> + 20 wt% micro-ATH had the highest AC dielectric strength.

Researchers have discovered that nano- and micro/nanofiller composites have superior dielectric performance compared to micro filler materials. The addition of nanofiller in these composites is believed to prevent treeing progression. The inherent permittivity of fillers can affect the dielectric strength of composites. An epoxy composite with 10% nano-clay has the highest dielectric strength of 26.21 kV/mm. Also, 20 nm nanoSiO<sub>2</sub>-filled epoxy has higher dielectric strength than 40 nm nanoAl<sub>2</sub>O<sub>3</sub>-filled epoxy because the SiO<sub>2</sub> particles don't make the field stronger as much. To increase dielectric strength, it is essential to minimize the difference in relative permittivity and electrical conductivity between filler and base polymer.

Polymers classified as nano- and micro composite are those in which a small level of fillers that are nanoscale is distributed throughout the polymer in various ways according to weight percentages (wt%). The nanofillers that are added to the matrix are added in very small

amounts typically, 10 percent less than the weight. In contrast to conventional composites, also known as micro-composites, a significant level of micro-fillers is used, accounting for up to 50% of the material's overall weight [83].

Two more important things that Tanaka et al. [84] tried to compare between polymer nanocomposites and polymer micro composites are The size of fillers and the specific surface area of composites are crucial factors to consider. They did this to learn more about polymer nanocomposites. In comparison to micro composites, nanocomposites differ by three orders of magnitude in length and range in size from nanometres (less than 100 nm). Nanocomposites have a smaller distance between neighboring fillers due to a nine-order difference in their number density compared to micro composites. Nanocomposites have a filler specific surface area three orders of magnitude larger than micro composites. As a result, it is anticipated that fillers and polymer matrices would interact considerably more in nanocomposites.

Traditional micro composites can enhance mechanical and thermal properties of composite materials, but they can also compromise electrical properties. Remarkably, the combined electrical, thermal, and mechanical characteristics of the recently developed polymer nanocomposites have improved significantly [85]. Particularly for the high voltage insulating industry, these significant effects have a positive impact on electrical property enhancement.

Paul B. McGrath and Guoxiang Xu's study on polymer insulators found that they suffer from electrical and environmental aging, leading to deterioration in performance. The main issue is surface material tracking and erosion due to environmental contaminants, electrical aging stresses like leakage current and dry-band discharges, and environmental aging stresses like humidity, temperature changes, and UV radiation. Cracks were observed on the EPDM shed surface under similar environmental stresses. The SiR insulator, with a larger contact angle, is less affected by these stresses [86].

Researchers [87-89] have discovered that adding nano-sized inorganic fillers to polymer insulation can improve its electric properties. They studied a material called XLPE/MgO nanocomposite, which combines MgO nanofiller with cross-linked polyethylene. The study found that adding nanosized MgO to XLPE increased its volume resistivity and stopped packet-like charges from happening in high electric fields. This effect was the same for both LDPE and XLPE. The results suggest that XLPE/MgO is an excellent material for high-voltage DC

insulation, making it suitable for high voltage distribution applications.

## 6.2 Enhancement of Mechanical Properties

The reliability of polymeric insulators is dependent on both electrical and mechanical properties. The side chain's mechanical properties are reduced due to oxidation and thermolysis, affecting their lifetime prediction at high temperatures and humidity. Researchers have attempted to improve this by incorporating fillers like SiR, EPDM, and epoxy into polymers [90].

Studies has looked at how the mechanical characteristics of polymeric composites are affected by the type, size, shape, loading, and dispersion of the filler. For instance, incorporating h-BN nanoparticles improved epoxy and EPDM properties [91, 92]. Silicone rubber filled with SiO<sub>2</sub> and ATH particles showed higher tensile strength, attributed to stronger interfacial interaction. However, the irregular shape of fillers with a high particle aspect ratio limits the contents, preventing sedimentation and limiting tensile strength. Overall, understanding these factors can help improve the mechanical properties of polymeric composites [93]. BN-filled SiR has lower tensile strength than ATH-filled SiR due to its high aspect ratio, causing more composite defects. The tensile strength of a polymer increases with filler particles, depending on the interaction between the particles and the polymer base material [93].

Akbar and co-workers found that the interaction and dispersion of added particles (20 wt% micro + 2 wt% nano SiO<sub>2</sub>) in silicone rubber, along with hydrogen bonding between silanol and OH groups of SiO<sub>2</sub> and silicone rubber, can maintain good mechanical strength [94]. The addition of 20 wt% micro and 5 wt% nano SiO<sub>2</sub> to a SiR composite significantly altered its mechanical properties compared to EPDM and epoxy composites due to strong crosslinking and hydrogen bonding.

Another study by Tariq Nazir et al. [90] examined the effects of micro- and nanofillers on silicon rubber composites. They produced four samples, including pristine SiR, 30 wt% micron-sized silica/SiR (MC), 27.5 wt% micron + 2.5 wt% nano silica/SiR (NMC), and 5% nano silica/SiR (NC).

Sunanda C. et al. [95] examined the mechanical properties of nano SiR composites, utilizing silicone rubber as a base polymer. They revealed that the tensile strength and elongation of SiR were reduced by MgO nanofillers at break but increased with higher nanofiller concentrations. ZnO nanofillers decreased SiR's tensile

strength and elongation at break but increased hardness by 12%. The insulating material's erosion resistance increased with filler concentration, and 10% of the ZnO sample was less susceptible to severe conditions.

Researchers in [96-98] have used nanofillers, specifically alumina and barium titanate, to improve the performance of SiR as an outdoor insulator. They used scanning electron microscope micrographs to ensure uniform dispersion and conducted the Inclined Plane Test for erosion. The study found that nanocomposites with BaTiO<sub>3</sub> filler were less likely to stick to surfaces, improved tracking and erosion resistance, and improved silicone rubber performance. Additionally, nano BaTiO<sub>3</sub> in SiR was found to be a more effective nanofiller compared to nanoAl<sub>2</sub>O<sub>3</sub>.

Researchers in [99-101] studied the impact of filler mixtures on SiR composites' ability to conduct heat, be strong, and not conduct electricity. They created micro-Si<sub>3</sub>N<sub>4</sub> and nano-AL<sub>2</sub>O<sub>3</sub>-filled SiR composites with varying amounts of Si<sub>3</sub>N<sub>4</sub> and AL<sub>2</sub>O<sub>3</sub> and hot-molded them. A 30% volume mix of nano AL<sub>2</sub>O<sub>3</sub> and micro-Si<sub>3</sub>N<sub>4</sub> made the composites better at conducting heat, having low dielectric permittivity, and being strong when they were broken. The inclusion of micro nano-sized particles enhanced the tensile strength and break elongation.

### 6.3 Enhancement of thermal Properties

Insulating materials are known for high thermal conductivity, but most polymeric materials have a thermal conductivity below 0.5 W/m.K, potentially leading to degradation during dry band arcing at higher temperatures [102]. Two methods to improve thermal conductivity include using intrinsic thermal conductive polymers with a highly ordered molecular chain structure, which are limited in electrical equipment due to high costs and complex manufacturing processes, and composite polymers with higher conductivity fillers. The factors influencing thermal conductivity in composites, addressing issues related to filler size, content, shape, orientation, surface treatment, and manufacturing method. Research has shown that adding micro- to nano-fillers and their hybrids can improve the thermal conductivity of polymers. A study on silicone rubber filled with micro-ATH, AlN, and h-BN showed that the thermal conductivity of h-BN-filled rubber was significantly higher than unfilled rubbers, with the highest enhancement attributed to improved cross-link points between hydrophilic OH groups and Si-o-Si functional groups [103].

The effect of filler size on the thermal characteristics of epoxy containing h-BN particles of micro- and submicron size was investigated by Heid and others [104]. They discovered that for the same weight percentage of each filler, sub microparticles enhanced heat conductivity by 6%. Thermal conductivity improved with increasing filler content as filler size decreased from micro to nano [105]. High aspect ratio fillers also contribute to the formation of high thermal conductivity composites [106]. However, because of increased porosity, increasing filler volume with bigger filler particles reduces heat conductivity [97]. According to the study, increasing the thermal conductivity of composites does not depend on the size of the filler [107].

Scientists [26, 108, 109] studied the thermal properties of SiR composites loaded with nanosized SiO<sub>2</sub> when exposed to AC voltage and ammonium chloride. They found that the thermal properties improved with an increase in filler percentage, but thermal aging slightly reduced tracking and erosion resistance. This is particularly concerning for electrical insulations, as UVC radiation poses a significant risk to human health and other earthly objects, including electrical insulation. Thermogravimetry Derivative Thermogravimetric (TG-DTG) studies were conducted to comprehend the impact of varying filler quantities on the thermal characteristics of the composites.

The study [110] analyzed silicone rubber insulators' deterioration after being exposed to UVC light and a contaminated solution. The polluted solution significantly increased leakage current, surpassing the impact of UV radiation alone, and the combination of UVC radiation and pollution was particularly significant. The aging process shifted the insulation's thermal deterioration temperature and degraded the polymer surface, particularly around the filler. UVC aging enhanced leakage current, but UV radiation alone was insufficient.

Researchers [111, 112] conducted inclined plane tracking and erosion tests on micron and nanosized particles filled with silicone rubber samples. They mixed alumina fillers into the silicone rubber matrix to improve tracking and wear resistance. Thermo Gravimetry Derivative Thermo Gravimetric (TG-DTG) studies were done to find out how the thermal properties of silicone rubber composites changed when different amounts of nano-sized SiO<sub>2</sub> filler were added. Results showed that the thermal properties of nano-filled virgin and aged silicone rubber samples improved with an increase in filler percentage. However, thermal aging slightly reduces the tracking and erosion resistance of nano-filled silicon

rubber composites. Ultraviolet (UV) ageing is a significant issue for electrical insulations, as UVC radiation, with its wavelength less than 290 nm, poses a significant risk to human health and other earthly objects, including electrical insulation.

Scientists B. Venkatesulu et al. did a study on how magnesium dihydroxide (MDH) and alumina trihydrate fillers that are very small could be used to make RTV silicone rubber less likely to catch fire. The study compared MDH and ATH silicone rubber composites using an inclined plane tracking and erosion resistance tester, finding MDH-filled composites performed better in terms of eroded mass, depth, width, and length. The MDH composite lost 49.8% of its mass compared to the ATH composite. This was because the MDH nanofillers had a larger surface area and were more stable at high temperatures. The results showed that at this low filler concentration, the MDH composite has performed better than ATH filler. Also, TGA results showed that MDH composite was more thermally stable.

The researchers [113, 114] talked about how inorganic fillers in silicone rubber dielectrics improve their thermal conductivity, relative permittivity, and electrical conductivity. This makes them useful for high-voltage insulation applications outside. When ATH or silica fillers are added to silicone elastomers, they create binary composites that conduct heat better. This was studied in terms of the type of filler, particle size, shape, and concentration. The composites were then used as a shell for polymeric insulators to stop material loss at dry band arcing sites by lowering the hot spot temperature.

## 7 Applications

### 7.1 Transformer Insulation

polymers such as epoxy resins, polyester, silicone, and imides are frequently used in dry transformers and electric machines as shown in **Fig. 3** [6]. Transformers used in high fire protection areas like oil depots, high-rise buildings, and airports are reinforced polyester with glass filaments. They enhance load resistance and provide robust resistance against infringement. These tapes are suitable for leaded insulation wires, external protection, and cable winding [118]. Silicone transformer oil is utilized as a coolant in high-voltage power transformers due to its high heat capacity, low viscosity, and dielectric strength, while polyester amide imides offer long-term endurance and high heat resistance for wire insulation [119].



**Fig. 3** Epoxy-resin cast dry type transformer.

### 7.2 Insulated Power Cables

Polymers like PE, HDPE, LDPE, and EPR are widely used as insulation materials in power cables. LDPE was the most widely used until the 1960s, but cross-linked polyethylene (XLPE) is preferred due to its enhanced properties, such as efficiency and high temperature resistance, making it a preferred choice [115]. However, HDPE cables are replacing XLPE cables in advanced distribution systems because of their superior resistance to water and lightning strikes, as shown in **Fig. 4** [116].

The research now focuses on enhancing the dielectric properties of nanocomposites by applying nanoparticles, which can improve mechanical strength, thermal stability, and resist dielectric breakdown. [117]. The focus is on developing insulating cables with unique properties for high temperatures and electric stress levels. The copolymer, free from cross-linking byproducts, has electrical properties and is promising for clean insulation materials in HV components like HVDC cables [118]. Additional methods for enhancing polymeric cables under the HVDC include the creation of nanocomposites and the incorporation of inorganic particles [48, 119].



**Fig. 4** Power cable.

### 7.3 High Voltage Transmission Line Insulators

Polymer insulators have become increasingly popular in high-voltage transmission systems due to their compact design, high mechanical strength, low maintenance, and simplicity of installation. They are made from silicon organic rubber and have been used since the early 1970s as an appropriate replacement for glass and porcelain insulators. Among the polymers used as insulators are silicon rubber, ethylene propylene, and EPR. **Fig. 5** shows a polymer suspension insulator used for high-voltage lines.

Researchers [40, 120] are now focusing on developing stress-reduction strategies using advanced technology materials. There are two primary grading systems: resistive and capacitive. Fillers are incorporated into the host matrix during capacitive grading to increase the dielectric material's permittivity. This changes the way the electric field is spread on the overhead insulators. In resistance grading, an inorganic filler is added to the base polymer to make a non-linear conductor. The nonlinear grading material becomes conductive when the strength of the electric field reaches a level that can withstand it, homogenizing the electric field and eliminating the enhancement effect.



**Fig. 5** Polymer suspension insulators.

### 8 Challenges and future directions

Over a century, insulating materials have evolved, ranging from pure polymers to nanocomposites, enhancing their mechanical, thermal, and electrical properties. For instance, there has been an increase in the electrical strength of materials at low temperatures. By ninefold, the withstand temperature of materials has increased 15 times. Furthermore The thermal conductivity and the breakdown strength of materials increased by 30 and 3000 times, respectively [121]. Despite advancements in dielectric properties, there are still challenges and problems, particularly in understanding the fundamental chemistry and physics behind these advancements.

The understanding of polymer nanocomposites and interface modifications is limited due to inadequate development, poor nanoparticle dispersion, and poor

experiment repeatability, resulting in the refinement of individual materials and improved composite performance and biodegradability challenges.

This research explores new directions for insulating polymers, improving interface modification and manufacturing technology, and investigating novel dispersion and surface modification techniques for nanomaterials. It also analyzes interface formation using computer calculations and analog simulations, designs multilayer technologies, and provides components for simpler and smaller applications [122]. Furthermore, biodegradable polymers' conductivity will be greatly enhanced by the addition of useful nanofillers to a polymer matrix, such as graphene. Developing nanostructured materials for ultra-capacitors, electro-optic, discharge-resistant high-voltage equipment, insulation, sensors, and actuators should be the main goal in terms of electrical applications.

### 9 Conclusion

A study on polymeric materials used in high-voltage transmission line insulators has identified silicone rubber as the most promising material. This paper explores the application of polymer materials, thermoplastics, and thermosets in electrical apparatus applications. Researchers have incorporated micro, nano, and combined micro/nano inorganic fillers into the basic polymer to enhance the life expectancy of these insulators. This composite enhances properties such as mechanical strength, corona-discharge resistance, tracking/erosion resistance, thermal conductivity, and dielectric strength.

Thermal conductivity in polymers refers to the interaction between the polymers and their fillers, with significant properties because of the disjointing of thermally conductive fillers at low filler loadings. Raising the temperature can change the characteristics of polymers, and factors such as environmental effects, electrode effects, temperature, voltage application, and frequency affect their dielectric strength. Current research focuses on developing nanofiller-added polymers with enhanced mechanical strength and decreased electrical erosion. Researchers are identifying suitable fillers and optimal loading levels to extend product life expectancy, enabling global manufacturers to produce better products in diverse global environments.



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