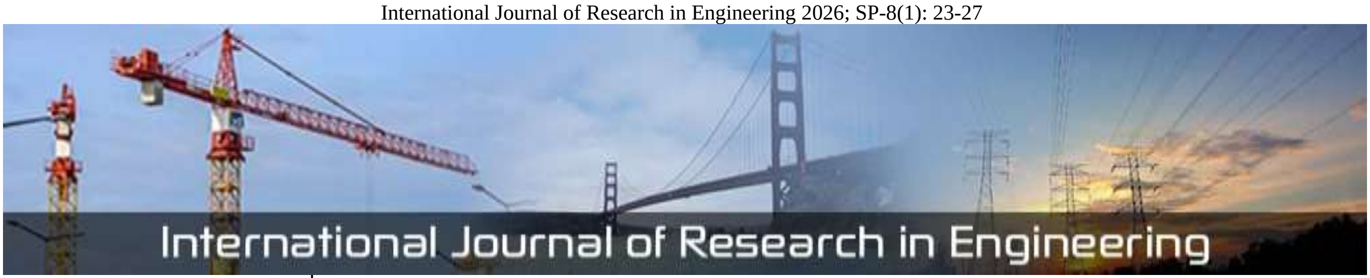

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The role of polymer composite with high voltage applications

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Abstract
The high-voltage insulation applications of low-density polyethylene (LDPE) and its nanocomposites have become increasingly important due to their superior dielectric and thermal performance. This paper reviews recent progress in LDPE-based polymer nanocomposites with respect to power engineering aspects, namely permittivity, breakdown strength, thermal conductivity, and aging behaviour. We then proceed to elaborate on the mechanisms for dispersing nanoscale fillers to maximize electric-field utilization, reduce space charge, and improve thermal transport, with only minimal loss of mechanical toughness—by comparing existing mixing rules with experimental observations of interfacial polarization. This work combines nonlinear conductivity and field-enhanced conduction by considering filler-induced modifications to trap states. The increase in breakdown strength (15-40% of the virgin value) is attributed to energy losses at filler sites, charge trapping, and crack-arrest effects. Thermal management and percolation-driven improvements in conductivity at filler loadings>~15-20% are also covered. Finally, the study addressed long-term thermal stability and the dual role of fillers as catalysts and stabilisers in polymer oxidation. The dielectric and thermal properties of LDPE containing various nanofillers. Their major applied areas, including environmentally friendly HV cables, transformers, and rotating machines, are reviewed, together with various challenges such as filler dispersion and economic upscaling. Finally, emerging strategies based on hybrid fillers, graphene-based filler methods, and novel interface engineering are proposed toward next-generation thermal insulation. This study will help orient research on LDPE nanocomposites for ultra-high-voltage power systems.

Keywords: Thermoplastic, Low-density polyethylene, Nanocomposites, Dielectric properties, High-voltage insulation, Nanofillers, Power system applications

Introduction
Electromagnetic stresses are increasing in contemporary power transmission systems. As a result, such a demand for insulation with high dielectric strength, good thermal stability, and long-term chemical stability has been growing. For many years, traditional insulation materials have shown good reliability. However, they will lack the performance required for compact AC and DC systems designed for high power. As voltage demands increase, insulators need to exhibit low electrical losses, suppressed space charge, and good heat dissipation. Consequently, several polymer-based nanocomposite systems that fulfill these requirements while simultaneously providing benefits not achievable with traditional polymers or microfilled composites have been investigated [1].

Nevertheless, low-density polyethylene (LDPE) remains one of the most widely used polymers for HV insulation due to its properties, such as low dielectric loss, high resistivity, and moderate moisture resistance. Pristine LDPE, on the other hand, exhibits low thermal conductivity, high efficiency of spatial charge-accumulation, and poor thermo-oxidative stability. Such limitations have spurred the development of innovative LDPE-based nanocomposites, whose interfacial charge-transport properties are altered at the nanoscale by the proper incorporation of nanoscale fillers, thereby enhancing dielectric, mechanical, and thermal properties [2].

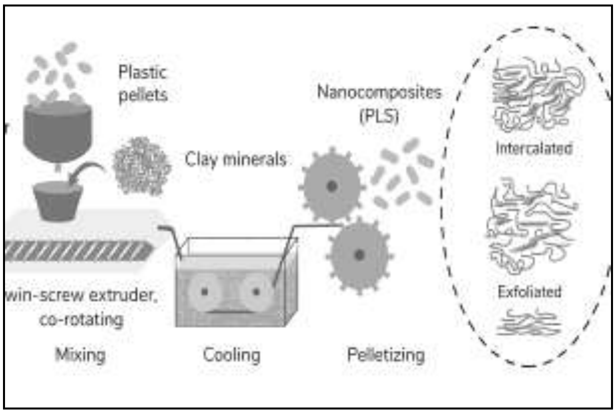

Fig 1: Simulation of a polymer-clay nanocomposite microstructure.

Figure 1 is a representative microstructure of a polymer-clay nanocomposite, showing some of these nanostructural changes. In the melt, layered silicates disperse in LDPE via an intercalated or exfoliated structure based on the extent of polymer stereoscopic penetration paths to interlayer spaces and the efficiency of the shear mixing mechanism.

These nanostructures significantly increase the polymer-particle interfacial area and influence the dielectric behaviour. While the addition of high−κ fillers (TiO_2, SiO_2, ZnO, AlN, etc.) improves permittivity above classical predictions because of Maxwell−Wagner interfacial polarization, suitable dispersion can increase dielectric loss. On the other hand, agglomeration creates unwanted conduction paths; thus , surface treatment and homogeneous dispersion are vital to high-voltage performance [3].

Nanofillers also suppress the nonlinear field-dependent conductivity (caused by Poole-Frenkel emission), which is pronounced in pure LDPE, where conduction is enhanced under high electric fields. The deep and shallow trap() introduction at filler interface, lowering (< 10 cm4 /s) the charge mobility (/\ of chargesiso). High charge mobility reduces space-charge accumulation, which is a key specification of HVDC insulation [4].

Here, usually 15-40% improvements in breakdown strength arise from crack-arresting effects of rigid fillers, localized energy dissipation, and charge trapping at interfaces. The most substantial enhancement occurs in hybrid systems such as AlN-SiO_2 due to synergistic interfacial interactions. Similarly, it can significantly enhance the final thermal conductivity by dispersing thermally conductive fillers in the polymer, forming percolating networks that help reduce hot spots and slow thermal ageing [5].

Though promising, addressing the challenges of nanoparticle dispersion, interface stability, and processing is required for the scalable production of LDPE nanocomposites; however, despite these drawbacks, the excellent dielectric, electrical, and thermal properties of the LDPE nanocomposites render them potential candidate materials for future high-voltage insulation applications, such as cables, transformers, and rotating machines [6].

Dielectric Permittivity and Loss

The effective permittivity of LDPE increases when high-κ nanoparticles are incorporated. A first-order mixing rule (Looyenga's formula) gives $\varepsilon c(1/3)=\varphi\eta f(1/3)+(1-\varphi)\varepsilon m(1/3)$, where φ = filler volume fraction [7]. On the other hand, in reality, the permittivity is more often than predicted associated with an interfacial polarization; an electrical double layer formed at the polymer-particle interface produces a Maxwell-Wagner polarization phenomenon. Tan (dielectric loss tangent ($\tan\delta$)) is often lowered at low filler loadings (due to carrier confinement). However, if agglomeration occurs, it may increase with higher loadings due to the introduction of additional loss pathways. Excess loss can be minimized by careful control of filler surface chemistry (e.g., hydrophobic coatings) and dispersion [8].

Electrical Conductivity and Field-Dependent Effects

The inherent DC conductivity of LDPE is extremely low at low fields. However, nonlinear conduction (field-enhanced carrier emission) is observed above ~1MV/m, which is modelled by a Poole-Frenkel effect $\sigma(E)=\sigma_0 \exp(\beta\sqrt{E})$ with $\beta \propto 1/\sqrt{\varepsilon\_r}$, and its suppression by nanofillers due to the introduction of new trap states and modification of trap state distributions effectively changing β [9]. LDPE nanocomposites may, however, show flatter σ-E curves than neat LDPE, thus indicative of less nonlinearity in practice. Hydrophobic). Surface-modified nanoparticles are particularly efficient at blocking conductive pathways at interfaces. Hence, this suppression of field-enhanced conduction is significant for HVDC applications [10].

Electrical Breakdown Strength

Dielectric breakdown strength is the highest field a dielectric can withstand without breaking down. Statistically, this is commonly characterized by a Weibull distribution with the scale parameter E_0 and the shape parameter [11]. With respect to pure LDPE, nanocomposite LDPE invariably achieves 15-40% higher breakdown strength, depending on the filler loading, dispersion quality, and interface properties [12]. Enhancement mechanisms include:

- Geometrical restraints: Stiff fillers restrict crack growth.
- Local energy dissipation: Stress is dissipated through higher dielectric losses in the vicinity of filler particles.
- Space-charge control: Trapping sites at material interfaces manipulate the charge distribution, mitigating local-field maxima.

In general, well-dispersed nanofillers behave as energy sinks, trapping charge and enhancing breakdown strength [13, 14].

Thermal Conductivity Enhancement

The thermal conductivity of pristine LDPE (0.4-0.5 W/m·K) is low. Thus, heat removal can be a limiting factor in high-voltage insulation [15]. Thermally conductive fillers (e.g., AlN, κ≈160-170 W/m·K) are often added to improve κ of the composite, but high κ values (>35 W/m·K) can be achieved only after exceeding a percolation threshold (15-20% filler by volume). Above this threshold, isolated particles can transfer heat poorly and provide limited benefit [16]. On the other hand, empirically, for composite κ fits a percolation type model $\kappa\_c=\kappa\_m(1+\alpha\ \varphi\text{^}n)$. It has been demonstrated that the use of high-aspect-ratio fillers (graphene nanoplatelets, boron nitride nanosheets) can maximize κ while enhancing network formation through surface functionalization or hybrid filler networks [17].

Thermal Stability and Aging

At operational levels (70-90°C for cables) and during transient heating, polymer insulation is degraded. Since LDPE undergoes oxidative chain scissions above ~200 °C, antioxidants (e.g., HALS, phenolic stabilizers) are typical additives [18]. The presence of nanofillers has also been cited as a determinant of thermal stability, as it is well known that the surface oxides on traditional melt-processed fillers (untreated fillers) can catalyze oxidation of the surrounding polymer. In contrast, inert or functionalized fillers may actually inhibit degradation. Hydroxylated silica or silane-treated alumina, for example, can effectively scavenge radicals, thereby slowing oxidation. Although long-term studies are limited, the key to reliability lies in selecting filler surfaces that do not promote accelerated aging. In this final interpretation, fillers and additives must be combined to withstand prolonged exposure to thermal stress [19].

Table 1: Dielectric and thermal properties of LDPE composites with various nanofillers (values at room temperature).

Nanofiller	Loading (wt%)	ε (1 kHz)	Breakdown (MV/m)	Thermal Conductivity (W/m·K)
Pristine LDPE	0	2.26	22.5	0.42
LDPE/AlN	15	2.68	28.3	1.24
LDPE/TiO_2	15	3.15	26.8	0.68
LDPE/SiO_2	15	2.45	25.2	0.58
LDPE/ZnO	15	2.87	27.4	0.92
LDPE/AlN-SiO_2 (8:7)	15	2.62	29.8	1.48

As shown in Figure 2, a comparative study of LDPE nanocomposites indicates that doping with inorganic nanofillers dramatically improves the dielectric, electrical, and thermal properties relative to pristine LDPE [20]. Among single-filler systems, LDPE/TiO_2 shows the most significant increase in dielectric constant, and LDPE/AlN shows a significant increase in thermal conductivity. For all nanofilled samples, the breakdown-strength enhancement increases in parallel, and the most significant increase was observed for LDPE/AlN-SiO_2, indicating interfacial synergistic effects in hybrid filler systems [21].

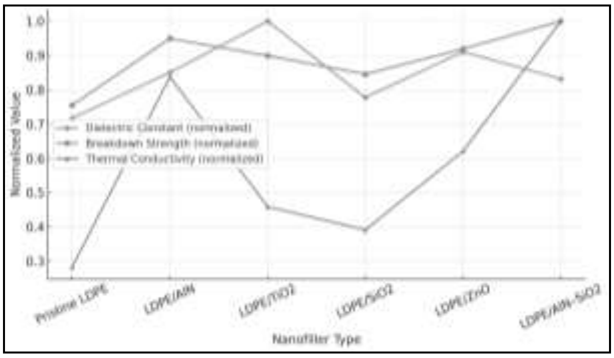

Fig 2: Comparison of LDPE Nanocomposites

Overall, the results show that thoughtful selection of nanofillers — especially strategic hybrid combinations — can adjust LDPE properties to enable high-performance electrical insulation and thermal management applications [22].

Power System Applications

High-Voltage Cable Insulation:

More than 80% of power cables use polyethylene insulation. Dielectric strengths above 50 MV/m (plus safety margin) for HVAC cables (33-400kV) and HVDC cables (± up to 800kV) require strict, complete resistivity control to mitigate space-charge buildup. Nanocomposite LDPE can provide better DC performance than traditional cross-linked PE (XLPE) cables, meaning less leakage under DC bias and better space-charge suppression (reducing the risk of electrical tree initiation and propagation). Cable design needs to consider insulation thickness (typically 6-15mm), filler loading, and cost against the performance targets [23].

Transformer Insulation:

Multi-layer oil-paper insulation is a standard application in modern transformers. At the same time, solid polymer composites are a newly emerging oil-free alternative. A higher breakdown strength of LDPE nanocomposites also provides full solid insulation without the need to fill insulating layers. Nano-fillers increase impulse breakdown strength and energy absorption, enabling these base materials to withstand a lightning impulse test (i.e., ~2-3× nominal voltage). In tightly wound transformers, the ability of high-thermal-conductivity fillers to absorb and dissipate heat can increase load capacity and life [24].

Rotating Machines (Generators/Motors)

High-voltage generators (≥10kV) employ slot liners with partial-discharge activity at 120-150 °C, containing LDPE composites with suitable thermal stabilizers for all weather conditions. The recurring thermal and mechanical loads imposed on the motor windings lead to crack initiation and propagation; the addition of nanoscale fillers (e.g., carbon nanotubes, clay particles) reinforces the tensile strength and modulus of the insulation, allowing it to withstand fatigue cracking. Fillers improve mechanical robustness and thermal stability, thereby extending generator/motor lifetimes under strenuous service conditions [25].

Challenges and Limitations

Nanofiller Dispersion

The most challenging task in this regard is achieving a uniform distribution of nanoparticles. Nanoparticles will agglomerate due to van der Waals forces, particularly at high loadings or with untreated surfaces. By serving as local field boosters and conductive pathways, aggregates degrade dielectric strength and increase losses. Whilst agglomeration can be reduced using more advanced dispersion methods (ultrasonication, surfactant blending, in-situ polymerization), these approaches tend to be complicated and expensive [26].

Interface Stability and Aging

Under sustained stress, the polymer-particle interface may deteriorate. At interfaces, moisture can be absorbed, leading to ionic contamination and the formation of new defect states or conduction paths. These interfacial evolutions aged the dielectric, leading to increased dielectric losses and a lower breakdown strength. They are also limited by long-term aging tests (electrical, thermal, mechanical); in particular, there is a need for additional accelerated-aging experiments and in-situ diagnostics (e.g., pulsed electroacoustic measurements) to evaluate nanocomposite reliability [27].

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Processing and Economics

Laboratory-scale methods (solvent mixing, meticulous melt compounding) and costly surface treatments are used in numerous nanocomposite investigations. Achieving this with constant quality when scaling up to industrial production is not trivial. For nanofillers, this is particularly problematic, as the purchase price is generally significantly higher than that of conventional fillers (up to 10-50× the cost) [28]. Thus, the performance increases must indeed justify this extra cost. Efforts are also underway to study fillers to reduce filamentation (percolation efficiency) or to develop processes that render nanodielectrics practical at reasonable manufacturing costs for large-scale applications [29].

Emerging Developments and Future Directions

The simulation of all-carbon nanomaterials (such as graphene) for dielectric applications is highly attractive to researchers. Pristine graphene is superconductive, whereas graphene oxide (GO) and polymer-grafted graphene have tunable dielectric properties along with high thermal conductivity [30]. The synergy between ceramic nanoparticles (AlN, TiO_2) and GO yields hybrid strategies that enhance breakdown strength and optimize thermal management. Interface engineering (silane/phosphonate coupling, polymer grafting onto nanoparticles, plasma treatment): promotes dispersion and adhesion [31]. A data-driven approach (design of experiments, machine learning) is applied to the vast filler/polymer design space to investigate and optimize trade-offs in dielectric, mechanical, thermal, and electrical performance [32]. Terahertz imaging and pulsed electroacoustic spectroscopy are developed as new diagnostics that provide insights into near-surface defects and charge behaviour in nanocomposites. In the future, the demand for insulation in ultra-high-voltage systems (for example, ±800kV UHVDC) will be tighter [33]. They are materials that ensure even charging and dissipate heat effectively. Nanocomposite insulator development toward these goals will depend on progress driven by empirically validated multiscale modeling.

Conclusions

Polymer nanocomposites based on low-density polyethylene (LDPE) represent a novel direction for the development of high-voltage insulation materials for next-generation applications. Nanoscale fillers, e.g., AlN, TiO_2, SiO_2, ZnO, and other emerging candidates, enable overcoming the limitations of the main dielectric properties of conventional polymers. Processing these nanofillers to achieve effective dispersion within the LDPE matrix can significantly enhance electrical breakdown strength, reduce space-charge buildup, and improve thermal conductivity at 0.5 (up to 1.0) wt% loading, while retaining the lightweight, flexible mechanical properties of polyethylene, making it suitable for potential power-system applications. Collection of these gains is necessary to provide reliable, yet energy- and cost-efficient, cables, transformers, power electronics, and rotating machines for numerous AC and more challenging HVDC applications.

However, these benefits are less straightforward to translate from the lab to commercialisation scale. Challenges such as uniformity in nanoparticle distribution and loading levels, overcoming thermodynamically unstable polymer-nanofiller interfaces, and developing efficient, low-cost manufacturing routes remain unresolved. Deployment is particularly complicated due to long-term aging and moisture resistance, as well as the need to be compatible with existing cable production lines.

To resolve these challenges, research is being conducted on multifunctional hybrid fillers, such as graphene derivatives, boron nitride nanosheets, and core-shell nanoparticles, which can also provide synergistic electrical and thermal benefits. Novel interface chemistries, such as surface-functionalized nanoparticles and molecular-level coupling agents, are designed to modify charge trapping, improve interfacial polarization, and enhance nanofiller stability under electrical stress. Progress in computational modeling, from molecular dynamics to multiphysics simulations, provides new insights into dielectric behavior and enables more detailed material optimization.

Integration of materials science, electrical engineering, and predictive modeling to continue this progress from the laboratory to functional, high-lifetime, energy-saving insulating materials will also be essential to support a strong, high-performance net-zero power grid.

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