

# Comparative analysis of nitride and oxide based nano fillers for polypropylene insulation

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## Abstract

Polypropylene (PP) is a promising insulation material for high-voltage direct current (HVDC) cables due to its electrical, thermal, and chemical stability. However, limitations such as high thermal expansion coefficient, low thermal conductivity, and poor flame retardancy restrict its direct application. This study investigates incorporating nano-scale oxide (MgO) and nitride (AlN) fillers into PP via solution blending to enhance dielectric performance. Nanocomposites with varying filler concentrations were prepared, and their AC breakdown strength and DC conductivity were evaluated. Results show that PP filled with 3 wt% AlN and 3 wt% MgO exhibited improvements in AC breakdown strength 15.4% and 13.82%, respectively compared to pure PP. DC conductivity analysis indicated reduced leakage current for nanocomposites at optimal filler concentrations, supporting their suitability for HVDC insulation. The incorporation of oxide and nitride nano-fillers into PP matrix enhanced electrical insulation characteristics, confirming these nanocomposites' potential for advanced HVDC cable applications

**Keywords:** aluminum nitride, breakdown strength, magnesium oxide, polypropylene.

**Data Availability:** All data supporting the findings of this study are available from the corresponding author upon request.

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## 1. Introduction

The global demand for electricity continues to grow rapidly, with annual electricity production expected to exceed 38,000 terawatt-hours by 2040, rising from 24,000 terawatt-hours in 2016<sup>[1]</sup>. In response to environmental concerns and the push for sustainability, renewable energy sources are projected to account for 51% of total electricity generation by 2040, a substantial increase from 22% in 2016. While this transition is essential for environmental preservation, it also poses new challenges for energy infrastructure, particularly in maintaining grid stability, efficiency, and long-distance power transmission.

To accommodate this shift, robust and sustainable power transmission systems must be developed. High-Voltage Direct Current (HVDC) transmission has emerged as a promising solution, particularly for long-distance and high-capacity energy transfer. Compared to High-Voltage Alternating Current (HVAC) systems, HVDC offers reduced transmission losses, lower line tower construction requirements, and faster repair times, making it highly suitable for overhead, underground, and submarine applications<sup>[2-4]</sup>. As global investments in submarine power cable projects increase, optimizing cable insulation materials becomes critical to improve performance and reduce energy losses.

Traditional HVDC cable insulation materials, particularly cross-linked polyethylene (XLPE), have limitations such as poor recyclability, high energy consumption during processing, and environmental concerns. These issues highlight the urgent need to explore non-cross-linked, recyclable, and environmentally friendly alternatives. Polypropylene (PP) has emerged as a strong candidate due to its favorable electrical, thermal, and chemical properties. PP maintains excellent electrical insulation regardless of humidity or frequency, exhibits high heat resistance (up to 373 K), and resists chemical degradation.

However, pure PP suffers from inherent drawbacks such as low flame retardancy, high thermal expansion, and poor thermal conductivity<sup>[5]</sup>. To address these limitations, researchers have focused on enhancing PP properties through nano-filler reinforcement, creating polypropylene-based nanocomposites.

Recent studies have explored the use of TiO<sub>2</sub>, ZnO, MgO, and AlN nano-fillers to improve PP's dielectric and thermal properties. For example, Li et al.<sup>[6]</sup> demonstrated that adding 3 wt% TiO<sub>2</sub> to PP significantly improves AC breakdown strength (up to 5.5 kV), while ZnO-based composites also showed higher dielectric strength under high-frequency AC voltage<sup>[7]</sup>. Similarly, Azrin et al.<sup>[8]</sup> reported that PP-MgO-

C8 nanocomposites exhibited up to 27.4% improvement in dielectric strength under DC stress compared to pure PP. Mazumde et al.<sup>[9]</sup> studied thermal conductivity improvements in PP nanocomposites by adding boron nitride (BN). The incorporation of plate-like BN particles improved heat dissipation while maintaining electrical insulation. This is critical for HVDC applications where temperature rise due to Joule heating can deteriorate insulation materials.

Similarly, Ruan et al.<sup>[10]</sup> showed that silica-coated AlN nano fillers in PP provided uniform dispersion, improved thermal conductivity, and reduced interfacial polarization, enhancing both dielectric and thermal properties. Wu et al.<sup>[11]</sup> established that the interface between polymer matrix and nano-fillers plays a vital role in trap formation, which helps suppress space charge. Surface modification techniques, such as silane treatment or organic functionalization, have been proven effective in reducing charge mobility and improving insulation longevity. Du et al.<sup>[12]</sup> also demonstrated that using surface-treated MgO nano fillers in PP not only increased trap density but also stabilized the dielectric constant, which is crucial for long-term operation under DC stress.

These studies collectively demonstrate that nano-filler-enhanced polypropylene materials offer a promising path toward high-performance, sustainable HVDC cable insulation. However, more comprehensive analysis is required to determine the optimal combinations and concentrations of nano-fillers for achieving superior electrical performance and long-term reliability. This research investigates the electrical characteristics of PP-based nanocomposites with various nano-filler loadings to identify suitable insulation materials for future HVDC cable systems.

## 2. Materials and Methods

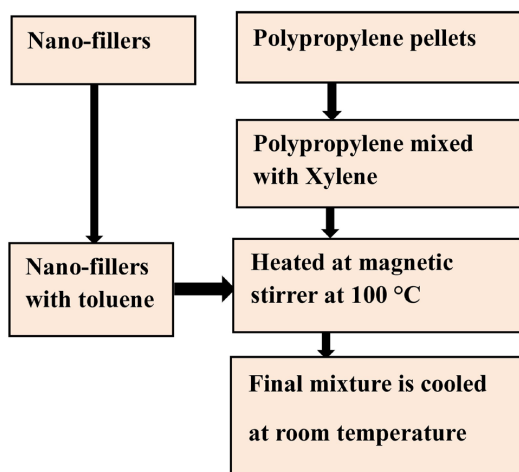
The material used in this study is isotactic polypropylene (iPP) (Sigma Aldrich), with temperature of 12g/10min, its isotopicity of 95%, and its melting temperature of 170°C. Two types of nano fillers were used. Aluminum nitride (AlN, 30 - 50nm) and magnesium oxide (MgO, 5 – 100nm) were obtained from Vedayukt India and Techinstro<sup>[13]</sup>. Figure 1 shows the flow chart for the preparation of the samples.

### 2.1 Sample preparation

To investigate the effect of different nano-filler loadings on the dielectric performance of polypropylene, six nanocomposite samples were prepared with varying concentrations of MgO and AlN: 2%, 3%, and 5% by weight relative to the PP matrix. The general preparation procedure involved dissolving PP in xylene, dispersing nano-fillers using toluene (for AlN), and employing magnetic stirring under controlled temperature and speed conditions.

To investigate the effects of nano-filler loading on the dielectric properties of polypropylene (PP), six nanocomposite samples were prepared using varying concentrations of magnesium oxide (MgO) and aluminum nitride (AlN). In all samples, 3 g of isotactic polypropylene was placed in a beaker and heated for 3 minutes using a magnetic stirrer to initiate softening. Following this, 10 mL of xylene was added as a solvent, and the mixture was stirred for 30 minutes to ensure complete dissolution of PP. For MgO-based samples, nano-filler concentrations of 2 wt%, 3 wt%, and 5 wt% were incorporated directly into the PP-xylene solution corresponding to 0.06 g, 0.09 g, and 0.15 g of MgO, respectively. Each mixture was subjected to continuous magnetic stirring at 350 RPM and 75°C for 1 hour and 15 minutes to ensure uniform dispersion of the nanoparticles. After processing, the solutions were cooled and left to solidify at room temperature for 24 hours.

For AlN-based samples, the same base PP-xylene mixture was prepared, after which AlN was separately dispersed in 2.5 mL of toluene and preheated at 100°C for 45 minutes under magnetic stirring to enhance dispersion. The prepared AlN dispersions, at concentrations of 2 wt% (0.06 g), 3 wt% (0.09 g), and 5 wt% (0.15 g), were then introduced into the PP solution. These combined mixtures were further stirred under identical conditions (350 RPM, 75°C, 1 hour 15 minutes), followed by 24-hour curing at room temperature. As shown in Figure 2, All six samples PP/2% MgO, PP/3% MgO, PP/5% MgO, PP/2% AlN, PP/3% AlN, and PP/5% AlN were then subjected to further physical and electrical characterization. Xylene was used for MgO dispersion due to its good solvency for PP and compatibility with metal oxides, whereas toluene was selected for AlN owing to its



**Figure 1.** Steps involved in sample Preparation.

favorable polarity for dispersing ceramic nitrides. These choices promote effective dispersion and matrix interaction.

The different contents of nano fillers and PP are presented in Table 1.

## 2.2 Characterization using Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) is observed for different prepared samples to find the presence of functional groups and to confirm molecular interactions between the polymer matrix and nano-fillers. In Figures 3 and 4, FTIR spectra for PP+3% AlN and PP+3% MgO nanocomposites. As expected, both spectra show prominent absorption peaks in the 2850–3000  $\text{cm}^{-1}$  range, corresponding to C–H stretching vibrations of the methyl and methylene groups inherent in the polypropylene backbone. The persistence of these characteristic peaks confirms that

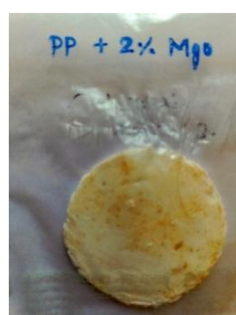
the chemical structure of the base PP matrix remains intact after the incorporation of nano-fillers.

While the nano-fillers themselves (AlN and MgO) are inorganic and do not exhibit strong IR-active modes in this region, their presence influences the polymer chain interactions. Notably, in both nanocomposite samples, subtle shifts in peak positions and variations in intensity are observed when compared to pure PP. These spectral changes although not indicative of covalent bonding suggest physical interactions and interfacial compatibility between the nano-fillers and the PP matrix. Such interfacial interactions are crucial for efficient stress transfer, dielectric enhancement, and suppression of charge accumulation in HVDC cable applications.

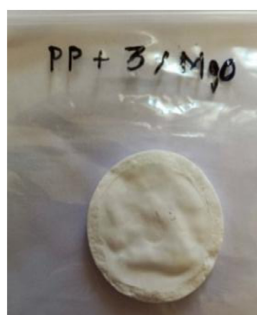
Furthermore, the selection of 3 wt% filler loading is supported not only by FTIR observations but also by our broader study results, including dielectric breakdown strength, thermal stability, and dispersion uniformity.

**Table 1.** Various samples under study.

Sample No	PP (wt.%)	Nano filler (wt.in grams)	Nano filler (wt.%)
1	100	0	0
2	98	0.06	2% MgO
3	97	0.09	3% MgO
4	95	0.15	5% MgO
5	98	0.06	2% AlN
6	97	0.09	3% AlN
7	95	0.15	5% AlN



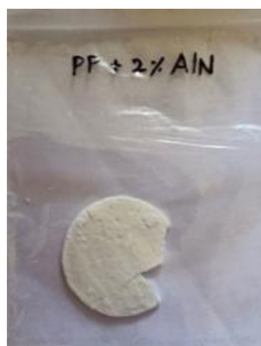
a) PP + 2% MgO



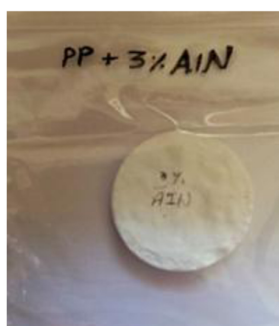
b) PP + 3% MgO



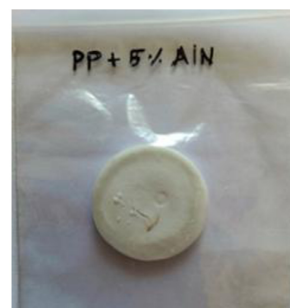
c) PP + 5% MgO



d) PP + 2% AlN



e) PP + 3% AlN



f) PP + 5% AlN

**Figure 2.** Photographs of all prepared polypropylene-based nanocomposite samples: (a) PP with 2 wt% MgO; (b) PP with 3 wt% MgO; (c) PP with 5 wt% MgO; (d) PP with 2 wt% AlN; (e) PP with 3 wt% AlN; (f) PP with 5 wt% AlN.

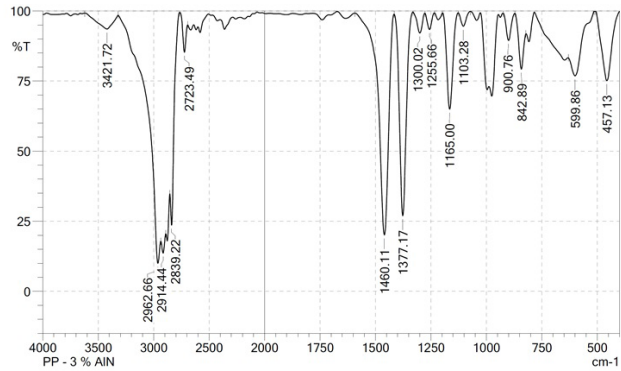


Figure 3. FTIR characterization of 3% AlN.

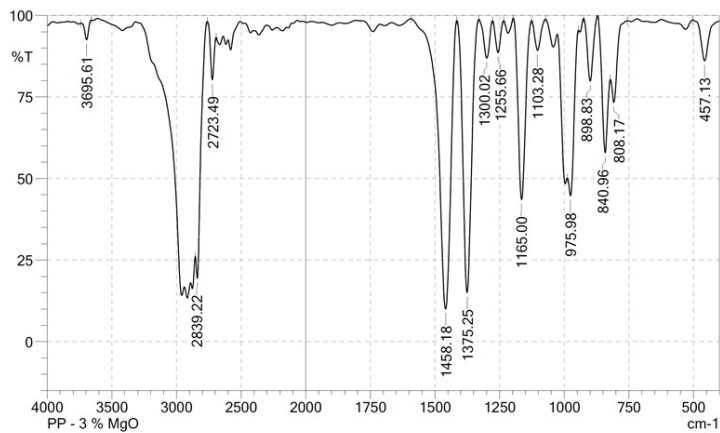


Figure 4. FTIR characterization of 3% MgO.

At this concentration, the nanocomposites exhibited an optimal balance between enhanced dielectric properties and processability. Higher filler loadings (5 wt%) tended to introduce agglomeration, which negatively impacts insulation performance and material homogeneity. On the other hand, lower concentrations (2 wt%) showed minimal improvements in electrical characteristics.

Thus, the FTIR analysis, in conjunction with other material characterization results, confirms that 3 wt% AlN and MgO filler concentrations are effective for achieving the required thermal and electrical performance needed in HVDC cable insulation applications. The findings are consistent with previous literature reporting<sup>[14-16]</sup> optimal nano-filler ranges for polymer-based dielectric composites.

### 2.3 Characterization using Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) was conducted to examine the morphology and dispersion characteristics of nano-fillers within the polypropylene (PP) matrix. The SEM images provide crucial insights into the microstructural uniformity, interfacial adhesion, and agglomeration behavior of MgO and AlN nanoparticles at various concentrations. Figures 5 and 6 show the SEM micrographs of PP+3% MgO

and PP+5% MgO composites, respectively, recorded at a magnification of  $\times 150$  with an accelerating voltage of 10.0 kV and a working distance of 11.0 mm. From these images, it is evident that the MgO nanoparticles are relatively well dispersed throughout the PP matrix, with minimal visible agglomeration. The homogenous distribution enhances the dielectric uniformity and contributes positively to the insulation performance of the nanocomposite.

Similarly, Figure 7 presents the SEM image of PP+5% AlN, captured at 20  $\mu\text{m}$  scale, using a 20.0 kV accelerating voltage and an 11.0 mm working distance. Figure 8 shows a higher magnification view at the 10  $\mu\text{m}$  scale for the same PP+5% AlN sample under identical voltage and distance settings. To quantify nano-filler dispersion, SEM images were analyzed using ImageJ software. Results confirm a uniform dispersion pattern at 3 wt% filler loading, with minor agglomeration observed at 5 wt%. In both images, the AlN nano-fillers are seen to be uniformly embedded in the PP matrix, indicating successful dispersion and matrix compatibility.

Importantly, surface modification of the nano-fillers using  $\gamma$ -methacryloxypropyltrimethoxysilane (MPS) played a significant role in achieving this uniform dispersion. The silane treatment enhances interfacial adhesion and prevents particle agglomeration, which is critical for maintaining

the electrical integrity and mechanical strength of the nanocomposite. The observed morphological uniformity in both MgO and AlN-filled composites confirms that particle–matrix compatibility is high, thereby minimizing localized field distortions and enhancing the dielectric performance—making these materials suitable for HVDC cable insulation applications.

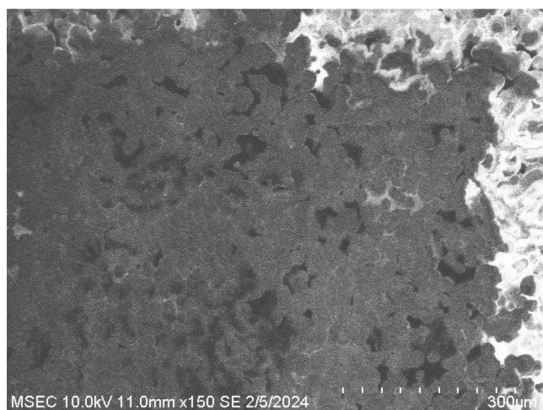


Figure 5. SEM image of 3% pp/MgO.

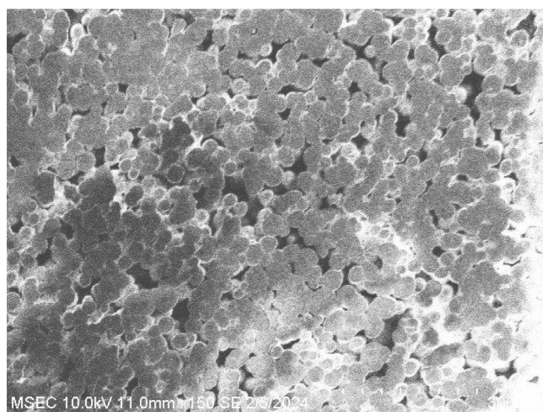


Figure 6. SEM image of 5% pp/MgO.

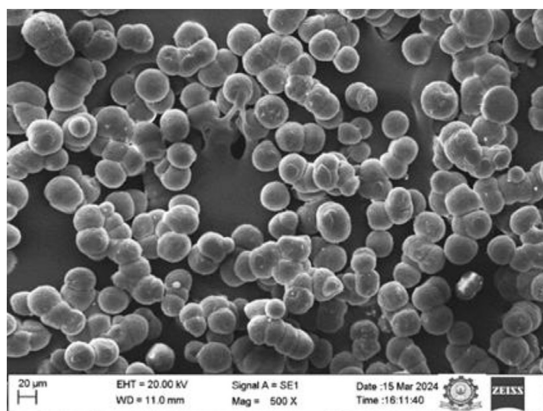


Figure 7. SEM image of 3% pp/AlN.

#### 2.4 Characterization using X-ray Diffraction (XRD)

As part of this study, X-ray Diffraction (XRD) analysis was conducted for all prepared nanocomposite samples to evaluate their crystalline structure, phase purity, and the effect of nano-filler incorporation on the crystallinity of the polypropylene (PP) matrix. As shown in Figures 9 and 10. The results revealed that the addition of nano-fillers significantly influenced the crystalline behavior of PP. Notably, the samples containing 3 wt% MgO and 3 wt% AlN exhibited enhanced peak intensities associated with the  $\alpha$ -phase of isotactic polypropylene, suggesting an improvement in overall crystallinity and ordered structure. This enhancement can be attributed to the nucleating effect of the well-dispersed nano-fillers, which promote the formation of smaller, more uniformly distributed crystallites.

The 3% filler concentration was found to be optimal, as higher concentrations (e.g., 5%) led to slight peak broadening and reduced intensity, indicating potential agglomeration and distortion of the polymer matrix, which may compromise dielectric performance. Conversely, lower concentrations (e.g., 2%) showed negligible changes compared to pure PP, suggesting insufficient interaction between the filler and the matrix.

The PP+3% AlN composite exhibited broader and less intense diffraction peaks compared to the PP+3% MgO composite. This suggests smaller AlN crystallite sizes or a higher degree of interfacial interaction with the polymer matrix, which may suppress sharp crystallinity. In contrast,

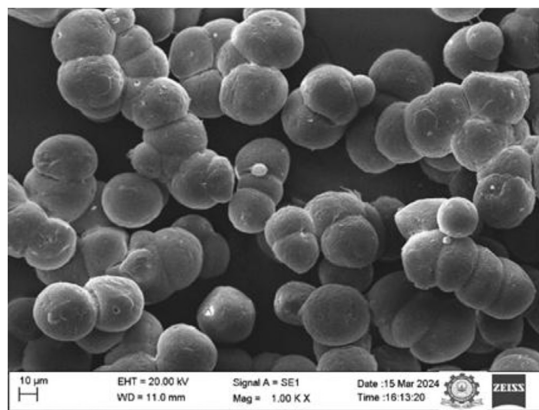


Figure 8. SEM image of 5% pp/AlN.

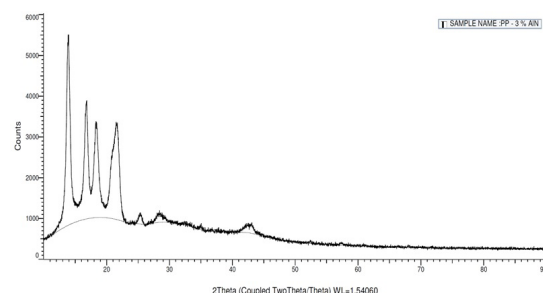


Figure 9. XRD characterization of 3% AlN.

the PP+3% MgO sample showed sharper and more distinct MgO peaks, implying relatively larger crystallite domains and slightly less interfacial distortion within the polymer network. This difference in peak sharpness and intensity may indicate that AlN particles are more uniformly dispersed and better integrated within the PP matrix than MgO at the same concentration. The suppression of peak intensity and slight broadening for both nanocomposites also suggest reduced PP crystallinity, potentially due to the physical obstruction and nucleation effects of the nanoparticles.

The improved crystallinity at 3 wt% MgO and 3 wt% AlN enhances mechanical stability, thermal resistance, and dielectric uniformity, all of which are critical properties for HVDC insulation applications. This optimal concentration ensures a balance between filler-induced nucleation and matrix compatibility, minimizing interfacial defects and enhancing long-term insulation reliability.

### 3. Results and Discussion

#### 3.1 AC breakdown test

The AC breakdown strength of the prepared polypropylene (PP) nanocomposite films was evaluated using a sphere-to-sphere electrode configuration. Samples with a uniform thickness of 100  $\mu\text{m}$  were immersed in silicone oil during testing to eliminate surface discharges and prevent flashover due to air exposure. A total of twenty measurement points were marked on each sample, ensuring consistent and statistically valid data. The samples were positioned carefully between the spherical electrodes, and AC voltage was applied at a ramp rate of 1 kV/s until dielectric failure occurred. The average breakdown voltage was recorded from multiple locations for each sample to obtain a reliable measure of dielectric strength. The results are presented in Figure 11.

Among the samples tested, PP + 3 wt% MgO exhibited the highest breakdown strength of 226.8 kV/mm, representing a 13.82% improvement over pure PP. Similarly, PP + 5 wt% MgO showed a breakdown strength of 219.24 kV/mm, which is 10.44% higher than that of the unfilled matrix. In contrast, PP + 2 wt% MgO yielded a slightly lower value of 185.71 kV/mm, approximately 6.14% below that of pure PP, likely due to particle agglomeration at this intermediate concentration.

For AlN-based composites, PP + 3 wt% AlN demonstrated a maximum breakdown strength of 230.34 kV/mm, reflecting a 15.4% enhancement over neat PP. However, the breakdown strength significantly declined with increased filler content. PP + 2 wt% AlN and PP + 5 wt% AlN exhibited lower values of 151.62 kV/mm and 172.83 kV/mm, which are 26.27% and 13.31% lower than that of pure PP, respectively. These reductions are attributed to filler agglomeration, which introduces interfacial defects, promotes localized electric field enhancement, and degrades dielectric performance at higher loading levels.

To further interpret the statistical variability of breakdown behavior, the Weibull probability distribution function was applied, expressed as:

$$P(E) = 1 - e^{-\left[\left(\frac{E}{E_0}\right)^\beta\right]} \quad (1)$$

where:

$E$ : the measured value of electric field at the different point of the sample;

$E_0$ : the critical parameter of the breakdown for a probability of 63.2%;

$\beta$ : the Weibull distribution shape parameter of the dielectric strength.

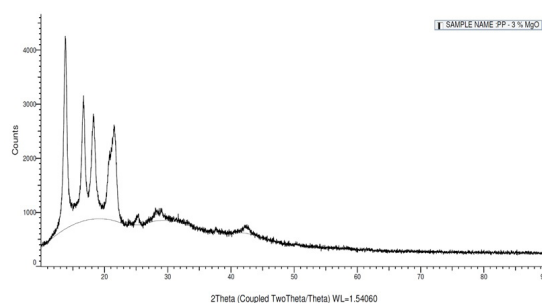


Figure 10. XRD characterization of 3% MgO.

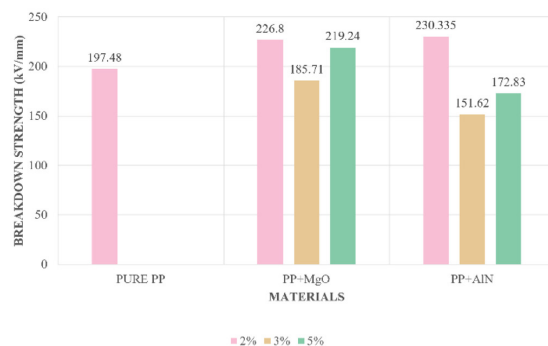


Figure 11. Average Breakdown voltage of Pure PP and PP with different concentrations of nano-fillers.

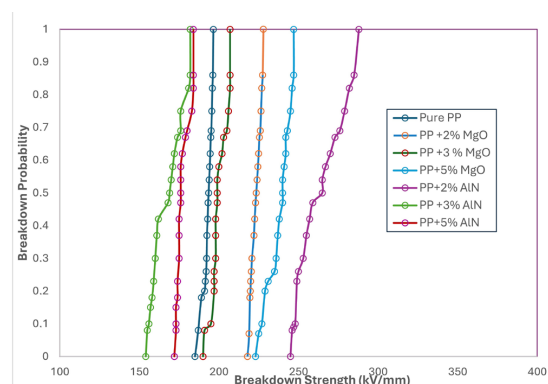


Figure 12. Weibull description of breakdown strength of PP/MgO/AlN nanocomposites.

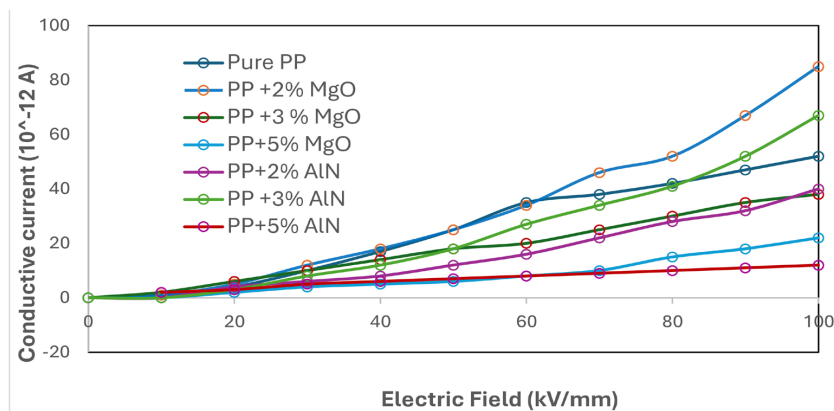


Figure 13. DC conductivity of samples under different electric field.

The Weibull model provides valuable insights into the reliability and uniformity of dielectric breakdown across the composite samples as shown in Figure 12. A higher  $\beta$ -value indicates narrower distribution and greater reliability, which can be correlated with better filler dispersion and interfacial bonding.

Overall, the results suggest that 3 wt% MgO and 3 wt% AlN are the optimal concentrations for enhancing AC breakdown strength, owing to a balance between improved crystallinity, dielectric uniformity, and minimal filler agglomeration. These findings demonstrate the potential of MgO and AlN-filled PP nanocomposites for high-voltage insulation applications in HVDC cables.

### 3.2 DC conductivity

The DC volume conductivity of the polypropylene (PP) nanocomposite films was measured using a digital high-resolution electrometer (Keithley) integrated with a standard three-electrode system, as per established protocols. The nanocomposite films, including PP/MgO and PP/AlN samples with a uniform thickness of 100  $\mu\text{m}$ , were subjected to DC electric fields ranging from 10 kV/mm to 100 kV/mm, applied in incremental steps of 10 kV/mm. Each voltage increment was maintained for 2 minutes, allowing the system to reach a quasi-steady-state condition before current measurement. Prior to the test, all samples were short-circuited for 10 minutes to eliminate any residual charge and ensure accurate baseline measurements.

This test procedure enabled the evaluation of the impact of nano-fillers on the bulk electrical conductivity of PP under high-field stress conditions<sup>[17]</sup>. The incorporation of nano-MgO and nano-AlN is expected to influence charge carrier mobility, trap density, and interfacial polarization effects, all of which contribute to the overall electrical resistivity of the composite.

The conductivity results, discussed in the following section, demonstrate how nano-filler type and concentration affect the DC volume resistivity of PP as shown in Figure 13. Improved dispersion and strong filler–matrix interactions at optimal loading (notably at 2–3 wt%) resulted in reduced leakage current and enhanced dielectric behavior, mak-

ing these nanocomposites suitable candidates for HVDC insulation applications.

## 4. Conclusion

Polypropylene (PP), owing to its high breakdown strength, elevated melting point, and recyclability, presents itself as a promising candidate for high-voltage direct current (HVDC) cable insulation. In this study, the incorporation of nano-scale oxide (MgO) and nitride (AlN) fillers into the PP matrix was investigated to evaluate their influence on the electrical properties of the resulting nanocomposites.

The results reveal that the breakdown strength of PP improved significantly at optimal filler concentrations. Specifically, the PP + 3 wt% AlN composite exhibited a maximum breakdown strength of 230.33 kV/mm, representing a 15.4% increase over pure PP. Similarly, the PP + 3 wt% MgO sample achieved a breakdown strength of 226.8 kV/mm, which is 13.82% higher than that of unmodified PP. However, further increasing the filler content beyond 3 wt% led to a decline in dielectric performance, likely due to agglomeration effects and interfacial imperfections.

Moreover, DC conductivity measurements confirmed that the addition of nano-fillers effectively reduced the conductivity of the composites, contributing to improved insulation performance. This reduction can be attributed to enhanced charge trapping and increased interfacial barriers introduced by the dispersed nano-fillers.

In conclusion, the study demonstrates that 3 wt% of AlN or MgO in a PP matrix offers an optimal balance of electrical properties, making these nanocomposites strong candidates for use in next-generation HVDC insulation systems. Future work may focus on long-term thermal aging, space charge behavior, and mechanical robustness to further validate field performance.

## 5. Author's Contribution

- **Conceptualization** – Sundaramahalingam Subramaniam; Manikandan Bairavan Veerayan.

- **Data curation** – Sundaramahalingam Subramaniam; Manikandan Bairavan Veerayan.
- **Formal analysis** – Sundaramahalingam Subramaniam; Manikandan Bairavan Veerayan.
- **Funding acquisition** – NA.
- **Investigation** – Sundaramahalingam Subramaniam; Manikandan Bairavan Veerayan.
- **Methodology** – Sundaramahalingam Subramaniam; Manikandan Bairavan Veerayan.
- **Project administration** – NA.
- **Resources** – Sundaramahalingam Subramaniam.
- **Software** – NA.
- **Supervision** – Manikandan Bairavan Veerayan.
- **Validation** – Manikandan Bairavan Veerayan.
- **Visualization** – Sundaramahalingam Subramaniam.
- **Writing – original draft** – Sundaramahalingam Subramaniam.
- **Writing – review & editing** – Manikandan Bairavan Veerayan.

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