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Simulation-Based Analysis of the Breakdown Strength of Different Dielectric Materials: A Comparative Study of Polymers, Ceramics and Composites

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ABSTRACT

In addition to the capacity to store and control electrical energy, dielectric materials are crucial to electrical and electronic engineering. These materials are distinguished by their insulating qualities, which are essential in circuit boards, capacitors, transformers and insulators, among other applications. This study presents a simulation-based analysis of the breakdown strength of various dielectric materials, focusing on polymers, ceramics, and composite materials using MATLAB. Dielectric breakdown strength is a critical parameter in determining the suitability of materials for high-voltage and high-frequency applications, such as power electronics, energy storage, and materials such as polyethylene (PE), polyimide (PI), alumina (Al_2O_3), barium titanate ($BaTiO_2$), and epoxy-resin-based composites infused with nanoscale fillers like silica (SiO_2) or carbon nanotubes (CNTs). The results highlight the unique strengths and limitations of these materials. Polymers like polyethylene exhibit high flexibility and process ability but are limited by thermal sensitivity. Ceramics, including alumina and barium titanate, offer exceptional thermal and electrical performance but suffer from brittleness. Composite materials demonstrate a balance of mechanical robustness and enhanced dielectric properties through tailored filler incorporation. This research identifies optimal material candidates with superior breakdown strength and provides valuable insights for the development of advanced dielectric systems in cutting-edge technologies, telecommunications. Using advanced simulation tools, this research evaluates and compares the dielectric breakdown mechanisms, thermal stability, and electrical performance of these materials, providing a comprehensive analysis of their applicability in advanced technologies such as telecommunications and power systems.

Keywords:
Breakdown strength,
Ceramics,
Composite materials,
Dielectric,
Dielectric materials,
Matlab,
Polymers

INTRODUCTION

Dielectric materials are essential in electrical and electronic engineering due to their ability to store and manage electrical energy (Chauhan *et al.,* 2021). These materials are characterized by their insulating properties, which are critical in applications such as capacitors, transformers, insulators, and circuit boards (Chen *et al.,* 2020). Dielectric materials are polarized in the presence of an electric field, allowing them to store electric charges effectively (Niu *et al.,* 2017).

The performance and reliability of dielectric materials are largely determined by their breakdown strength, which refers to the maximum electric field a dielectric material can withstand before experiencing electrical breakdown and thus results in the loss of its insulating properties (Ishikawa *et al.,* 2018). The breakdown strength of dielectric materials is a parameter that determines their performance and reliability in high-voltage and high-frequency applications. This property is critical in designing reliable electrical systems, as failures can lead to significant damage (Mazzanti *et al.,* 2013). Factors such as material purity, thickness, and operating temperature significantly influence the breakdown strength of dielectric materials (Lau *et al.,* 2013). Different dielectric materials exhibit varying breakdown strengths based on composition, thickness, temperature, and impurities. Polymers such as polyethylene and polypropylene are widely used for their good dielectric properties and flexibility, making them ideal for electrical insulation (Lee *et al.,* 2021). Ceramics, like alumina and barium titanate, offer high dielectric constants and thermal stability, suitable for high-voltage applications (Calame *et al.,* 2018). Composites that combine polymers with ceramics or other materials show promise in achieving superior breakdown (Kim *et al.,* 2020, Fan *et al., 2021*). Recent advancements in material science have led to the development of novel dielectric materials with enhanced breakdown strengths. Polymer nanocomposites, which incorporate nanoparticles into polymer matrices, have shown significant improvements in dielectric properties (Kim *et al.,* 2021). These materials benefit from the high surface area and enhanced interfacial interactions provided by nanoparticles, which improve overall performance (Wang *et al.,* 2021). Similarly, ceramic-based dielectrics are being optimized through microstructural modifications and the incorporation of dopants to enhance breakdown performance (Li *et al., 2019*).

Understanding the breakdown mechanisms and factors influencing the breakdown strength of different dielectric materials is essential for developing more reliable materials (Lee *et al., 2020*). The breakdown strength is influenced by external factors such as material purity, structural integrity, and the presence of defects (Maity *et al.,* 2020). Advanced characterization techniques, such as X-ray diffraction (XRD) and scanning electron microscopy (SEM), are used to analyse microstructural properties and identify causes of breakdown (Kalita *et al., 2019,* Zhao *et al., 2021*). These techniques offer detailed insights into material structure, guiding improvements in dielectric performance. When a dielectric material undergoes breakdown, it becomes conductive, potentially causing failures in electronic circuits and systems (Pinto *et al., 2020*). Therefore, understanding and enhancing the breakdown strength of dielectric materials is crucial for developing more reliable and efficient electrical systems (Ryu *et al., 2016*).

MATERIALS AND METHODS

Theoretical Framework

The underlying theoretical framework for this study involves several key principles related to dielectric materials, and the behaviour of breakdown strength of different dielectric materials.

Dielectric Constant

The dielectric constant (ε_r) quantifies a material's ability to store electrical energy in an electric field. Its temperature and frequency dependence can be modelled as (Mishra *et al., 2018*):

$$\varepsilon_r(T,f) = \varepsilon_{r_o} + \alpha(T - T_o) + \beta f \tag{1}$$

where ε_{r_o} is the base dielectric constant, α and β are coefficients that describe how temperature and frequency affect the dielectric constant

Loss Tangent

The loss tangent (tan δ) represents the energy dissipation within the material when subjected to an electric field. It can be modelled similarly as (Mishra *et al., 2018*):

$$\tan\delta = \tan\delta_o(1 + (T - T_o) + \delta f) \tag{2}$$

This relationship highlights the dependency of loss tangent on temperature and frequency

Resistivity

Resistivity (ρ) indicates how strongly a material opposes the flow of electric current. Its temperature dependence can be described by the Arrhenius equation:

$$\rho(T) = \rho_o e^{\frac{E_a}{k(T - T_o)}} \tag{3}$$

where E_a is the activation energy, and k is Boltzmann's constant (Mishra *et al., 2018*):

Simulation Parameters

Table 1: Simulation Parameters

Parameter	Value	Description	Unit
Number of conditions	30	Number of simulation points	-
Temperature	500 – 2000	Temperature range	ºC
Frequency	1kHz – 1GHz	Frequency range	Hz
Electric Field	0 – 500	Electric field range	MVm^{-1}
Materials	Polymer, Ceramic, Composite	Types of materials simulated	-
Base Dielectric Constant ε_{r_o}	2.5 (Polymer), 9.4 (Ceramic), 5.0 (Composite)	Initial dielectric constant values	-
Base Loss Tangent $\tan\delta_o$	0.02 (Polymer), 0.001 (Ceramic), 0.005 (Composite)	Initial loss tangent values	-
Base Resistivity ρ_o	1×10^{14} (Polymer), 1×10^{12} (Ceramic), 1×10^{13} (Composite)	Initial resistivity	Ohm.m
Dielectric constant coefficient α	0.005 (Polymer), 0.002 (Ceramic), 0.004 (Composite)	Temperature dependence factor for ε_r	-

Dielectric constant coefficient β	0.01 (Polymer), 0.02 (Ceramic), 0.015 (Composite)	Frequency dependence factor for ε_r	-
Loss tangent coefficient γ	0.001 (Polymer), 0.0005 (Ceramic), 0.0008 (Composite)	Temperature dependence factor for tanδ	-
Loss tangent coefficient δ	0.002 (Polymer), 0.003 (Ceramic), 0.0025 (Composite)	Frequency dependence factor for tanδ	-
Activation Energy E_a	1.1×10^{-19} (Polymer), 1.2×10^{-19} (Ceramic), 1.15×10^{-19} (Composite)	Used in resistivity calculation	J
Boltzmann Constant k	1.38×10^{-23}	Used for resistivity formula	J/K
Breakdown Threshold	300 (Polymer), 400 (Ceramic), 500 (Composite)	Electric field threshold for breakdown	MV/m

RESULTS AND DISCUSSION

The results of the simulation and analysis are presented below

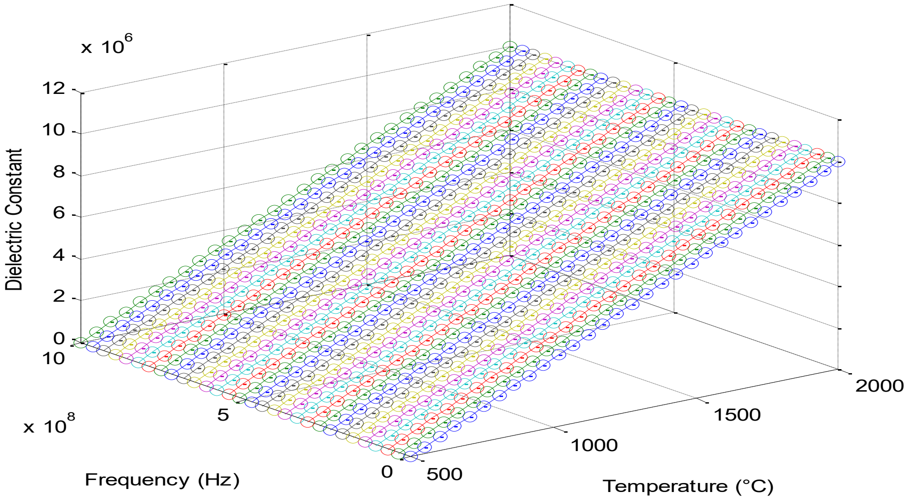

Figure 1: Dielectric constant vs. Temperature and Frequency (Polymer)

Fig. 1 shows Dielectric Loss vs. Temperature and Frequency (Polymer**).** Dielectric loss in polymers often increases with temperature and frequency. As the temperature rises, polymer chains gain more energy, leading to increased mobility of dipoles, which can enhance dielectric losses. Higher frequencies also contribute to dielectric losses due to the lag in dipole alignment with rapidly oscillating fields. At lower frequencies, polymers may exhibit lower dielectric losses at moderate temperatures, as dipoles have sufficient time to align with the electric field. However, as temperature increases, there's a point where dielectric loss rises sharply, suggesting a possible relaxation process. Higher frequencies accelerate this increase due to limited time for dipole alignment, indicating that at higher temperatures and frequencies, the polymer structure's energy dissipation is significantly affected. Considering Figure 1 and its discussion, it is evident that the dielectric constant does not depend on frequency but varies with temperature. This observation is applicable to all figures (Figures 1–9), except the breakdown figures (Figures 4, 8, and 12). The variation in dielectric constant with temperature suggests that material structure and polarization mechanisms are significantly influenced by thermal effects rather than frequency-dependent phenomena. This is consistently observed across the simulations, reinforcing the dominance of thermal factors over frequency variations in determining dielectric behaviour.

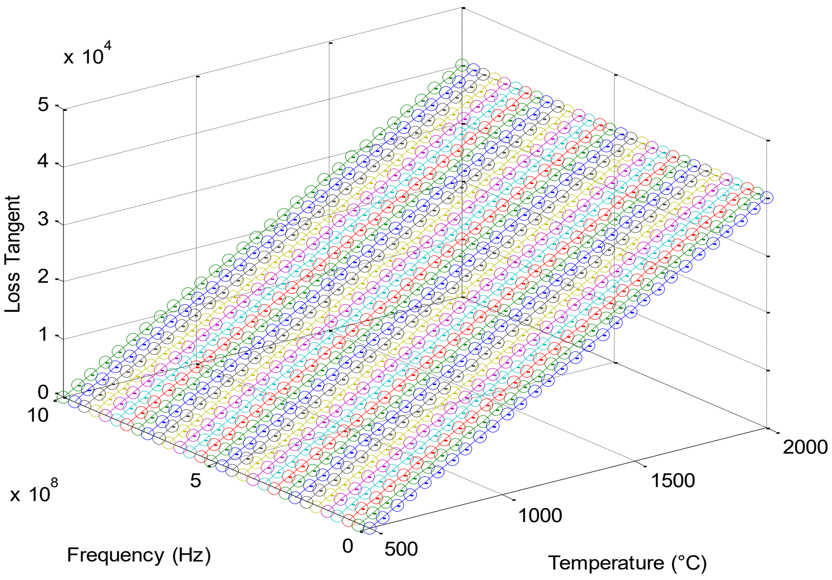

Figure 2: Loss Tangent vs. Temperature and Frequency (Polymer)

Fig. 2 indicates Loss Tangent vs. Temperature and Frequency (Polymer). The loss tangent, which is the ratio of dielectric loss to dielectric constant, shows how efficiently a material stores and dissipates electrical energy. For polymers, the loss tangent is expected to increase with temperature due to molecular agitation and mobility. Higher frequencies can also result in increased loss tangents due to dipole lag. The loss tangent has a peak at a characteristic temperature, known as the relaxation temperature, which represents the polymer's glass transition or relaxation point. Beyond this peak, the loss tangent may plateau or decrease slightly as the temperature-induced molecular motion starts to align out of phase with the electric field. This behaviour indicates that the polymer is approaching a disordered state, where dipole alignment with the electric field becomes less efficient.

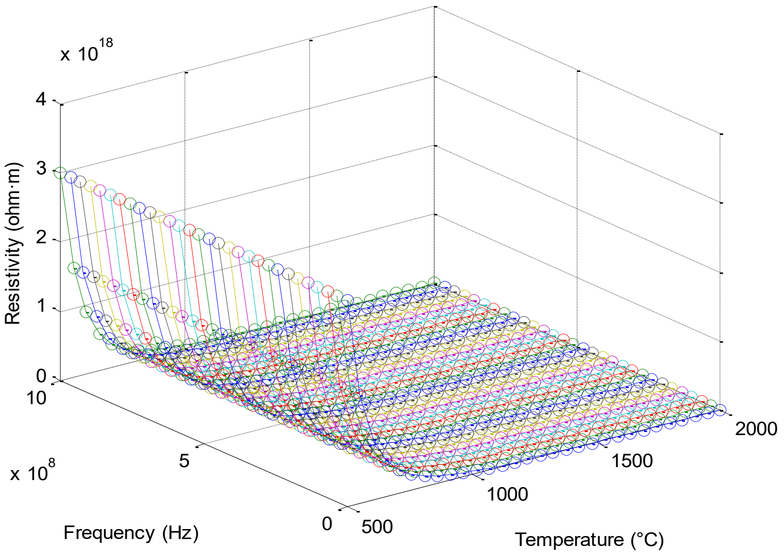

Figure 3: Resistivity vs. Temperature and Frequency (Polymer)

Fig. 3 **e**xhibits Resistivity vs. Temperature and Frequency (Polymer). Resistivity in polymers decreases as temperature increases, owing to increased thermal energy, which mobilizes charge carriers and facilitates conduction. At higher frequencies, resistivity might show variations due to the polarization and conduction processes' response to alternating fields. The polymer's resistivity drop with increasing temperature signifies enhanced charge mobility, typical for materials with thermally activated conduction. A higher frequency can add complexity, as polymer chains may not align fully with rapidly oscillating fields, potentially affecting charge carrier pathways and slightly impacting resistivity. This behaviour suggests polymers have a higher conduction component at elevated temperatures and lower frequencies, tied to ionic or electronic conduction mechanisms.

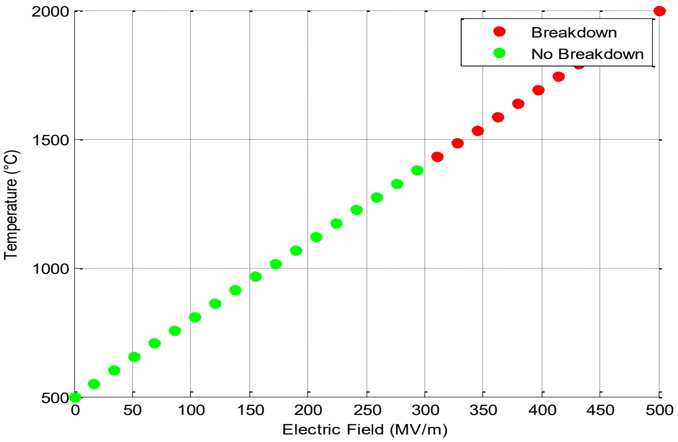

Figure 4: Breakdown Simulation of Polymer

Fig. 4 indicates Breakdown Simulation of Polymer. The breakdown simulation shows an increase in electric field strength with rising temperature up to a critical threshold. At lower temperatures (around 500°C), the polymer withstands modest electric fields, but as the temperature reaches higher levels (e.g., around 2000°C), the breakdown electric field reaches approximately 500 MV/m. The polymer's breakdown field strength increases steadily with temperature, indicating a progressive enhancement in its dielectric capability with temperature. This may be attributed to increased thermal motion, which allows the polymer molecules more freedom to align with the electric field up to a point. Transition to Breakdown: Beyond a certain temperature, the polymer shows a sharp decline in resistivity and increased energy dissipation (as observed from loss tangent values in the data). This suggests a thermal threshold where the material can no longer sustain its insulating properties. At temperatures above approximately 2000°C and high frequencies, the polymer likely reaches the limit of molecular stability, leading to dielectric breakdown as resistivity falls significantly, and the material loses its ability to withstand further electric field increases.

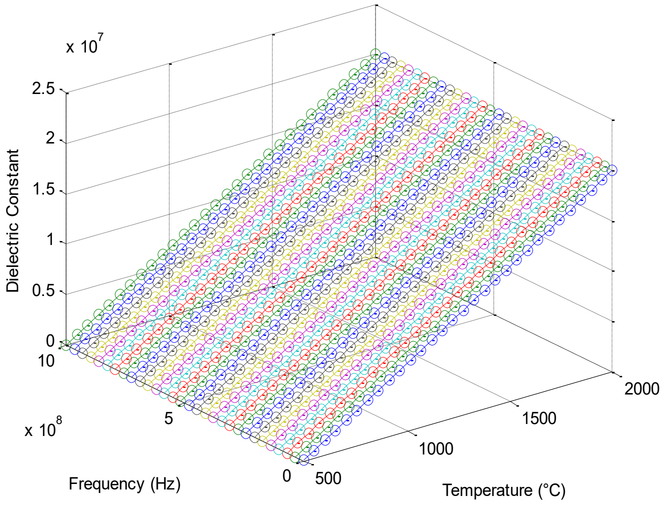

Figure 5: Dielectric constant vs. Temperature and Frequency (Ceramic)

Fig. 5 illustrates Dielectric Loss vs. Temperature and Frequency (Ceramic**).** Ceramics have lower dielectric losses compared to polymers, due to their rigid structure and lower dipolar mobility. Dielectric loss in ceramics increase with temperature as ionic polarization mechanisms become active but generally remains stable across a range of frequencies. For ceramics, temperature-induced dielectric losses may appear due to thermal excitation of ionic or electronic polarization. However, unlike polymers, ceramics are less responsive to higher frequencies because of their rigid, crystalline structures. The graph might show an increase in dielectric loss at high temperatures, indicating an onset of ionic conduction or relaxation phenomena. Thus, dielectric loss in ceramics is primarily influenced by temperature rather than frequency changes.

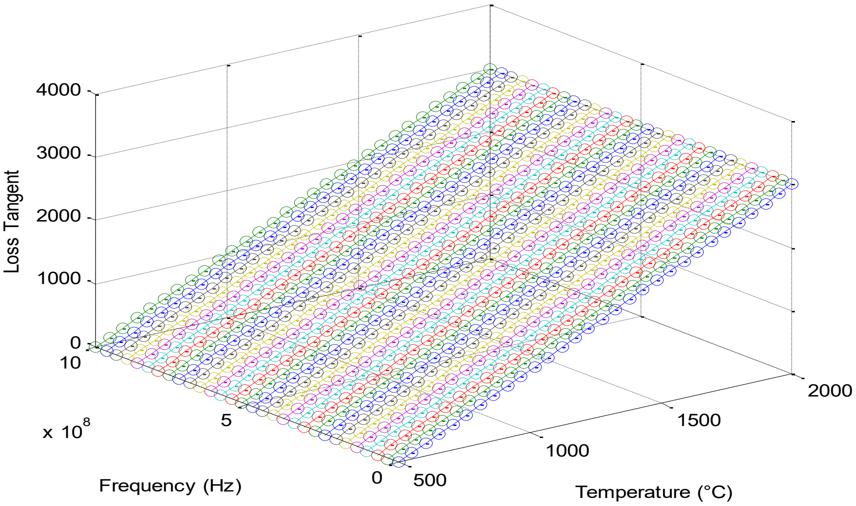

Figure 6: Loss Tangent vs. Temperature and Frequency (Ceramic)

Fig.6 **e**xpresses Loss Tangent vs. Temperature and Frequency (Ceramic). The loss tangent in ceramics increase modestly with temperature due to thermal activation of charge carriers. Higher frequencies might also raise the loss tangent, but less so than in polymers. In ceramics, loss tangent behaviour with temperature reflects the activation of defect or impurity-driven conduction paths. Frequency influence is often minimal unless the ceramic structure contains mobile ions, which respond to AC fields. A rise in loss tangent at specific temperatures can suggest the temperature range where ionic or defect polarization is prominent, hinting at intrinsic or extrinsic conductivity sources in the ceramic structure.

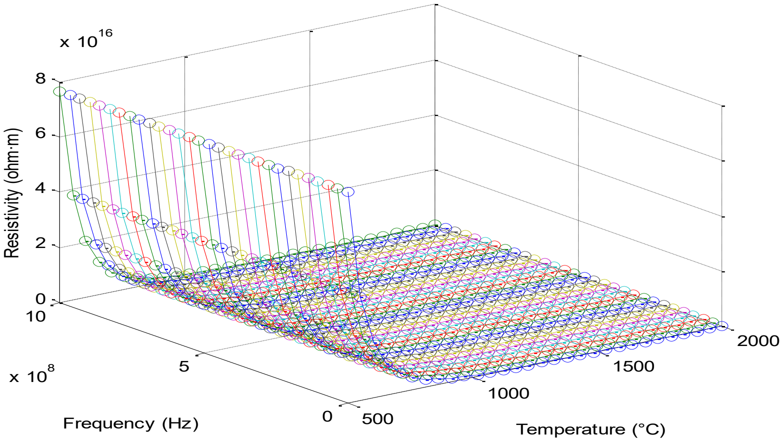

Figure 7: Resistivity vs. Temperature and Frequency (Ceramic)

Fig. 7 shows Resistivity vs. Temperature and Frequency (Ceramic). Ceramics, being good insulators, have high resistivity, which decreases with temperature due to thermally activated charge carriers. Frequency may not have a substantial effect on resistivity in ceramics unless ionic conduction becomes significant. The resistivity's drop with temperature in ceramics often reflects impurity or defect activation within the crystal structure. Frequency has a limited effect, though at high temperatures, increased oscillation rates may cause slight fluctuations in resistivity as ionic paths become more conductive. High resistivity at room temperature and its decrease with temperature indicates that ceramics rely on impurity or defect states for conduction.

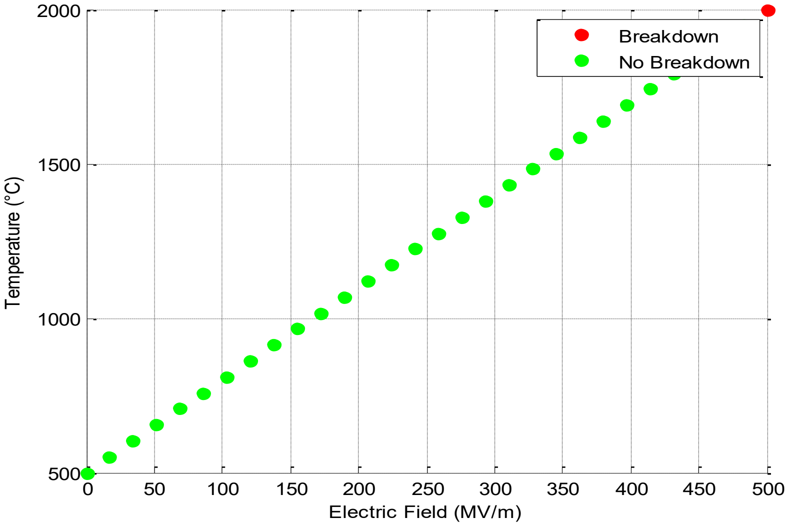

Figure 8: Breakdown Simulation of Ceramic

Fig. 8 indicates Breakdown Simulation of Ceramic Superior Breakdown Resistance: Ceramic materials exhibit much greater breakdown resistance compared to polymers. In this simulation, ceramic maintains a high breakdown field, reaching 500 MV/m around 2000°C, and shows no breakdown up until very high electric field levels. The ceramic's performance is largely due to its crystalline structure and high thermal stability, allowing it to withstand significant electric fields without structural degradation or excessive energy dissipation. Temperature Influence: Unlike polymers, ceramics typically display a more gradual response to temperature changes, with dielectric strength remaining relatively stable across a wide range of temperatures. The breakdown threshold for ceramics is reached at higher temperatures and higher field strengths, as reflected in the data, where ceramic resistivity remains high up to extreme temperatures. The gradual decrease in resistivity suggests that while ceramics are thermally stable, they eventually reach a point where intrinsic breakdown occurs, due to thermal activation of charge carriers at extremely high temperatures.

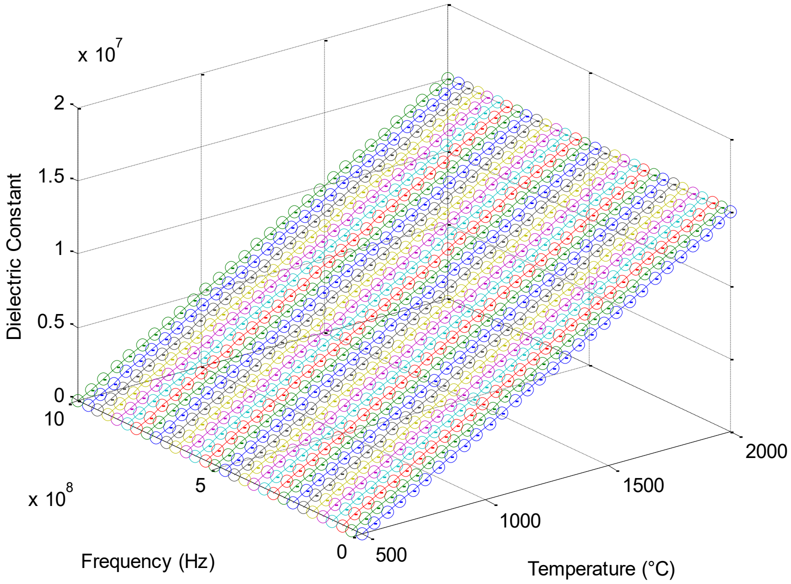

Figure 9: Dielectric constant vs. Temperature and Frequency (Composite)

Fig. 9 reveals Dielectric Loss vs. Temperature and Frequency (Composite). Composites, often combining polymer and ceramic properties, show an intermediate dielectric loss behavior. As temperature rises, dielectric loss increases due to polymeric components, with frequency also playing a significant role depending on the polymer-to-ceramic ratio. Dielectric loss in composites reflects contributions from both polymer (dipolar loss) and ceramic (ionic loss). The polymeric component causes higher dielectric loss at increased temperatures and frequencies. Composites exhibit a nuanced response, with dielectric loss highly dependent on composite material ratios.

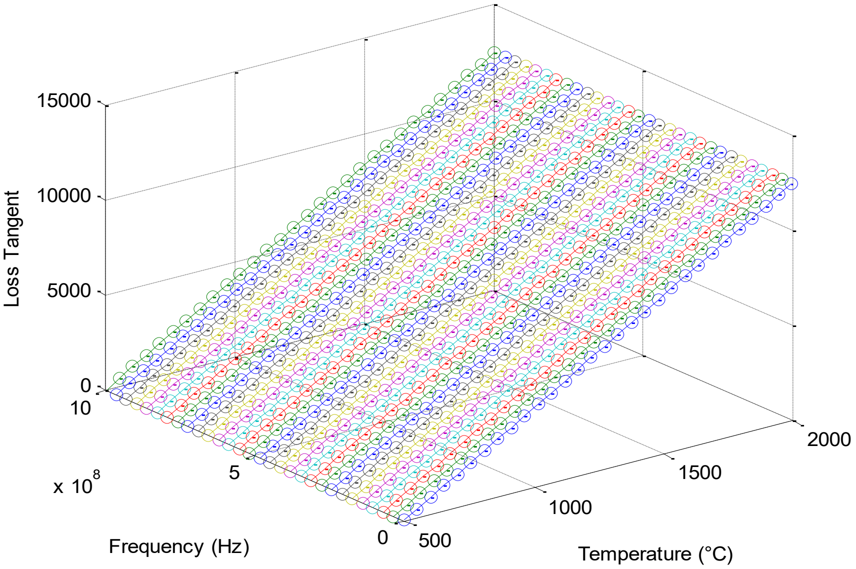

Figure 10: Loss Tangent vs. Temperature and Frequency (Composite)

Fig. 10 shows Loss Tangent vs. Temperature and Frequency (Composite). The loss tangent in composites can vary widely, peaking at temperatures indicative of relaxation phenomena within the polymeric phase. Higher frequencies generally increase the loss tangent, but the ceramic phase moderates this effect. The composite's loss tangent peak reflects the temperature where polymer components transition, which affects energy dissipation. Frequency response varies due to ceramic content, providing stability against high-frequency effects seen in polymers alone. This peak signifies the balance between energy storage (ceramic) and dissipation (polymer), with the composite benefiting from both low dielectric loss and efficient energy storage across a range of temperatures.

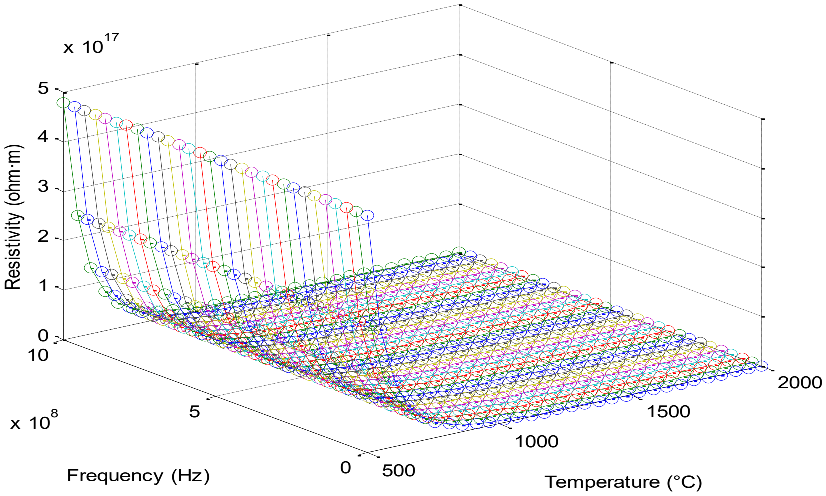

Figure 11: Resistivity vs. Temperature and Frequency (Composite)

Fig. 11 is a plot of Resistivity vs. Temperature and Frequency (Composite). Composite resistivity typically decreases with temperature, as the polymer phase allows more charge movement at higher temperatures. Frequency effects were less pronounced than in polymers but more noticeable than in ceramics. Composite resistivity shows an initial high value due to ceramic content but decreases with temperature, indicating the polymer phase's conduction role. Frequency might mildly impact resistivity, especially at high temperatures, as charge carriers in the polymer phase respond to AC fields. This behavior demonstrates the composite's hybrid nature, where the ceramic component maintains high resistivity at lower temperatures, and the polymer reduces resistivity at elevated temperatures. Each material's distinct phase properties (polymer, ceramic, and composite) create unique responses in dielectric loss, loss tangent, and resistivity across temperatures and frequencies.

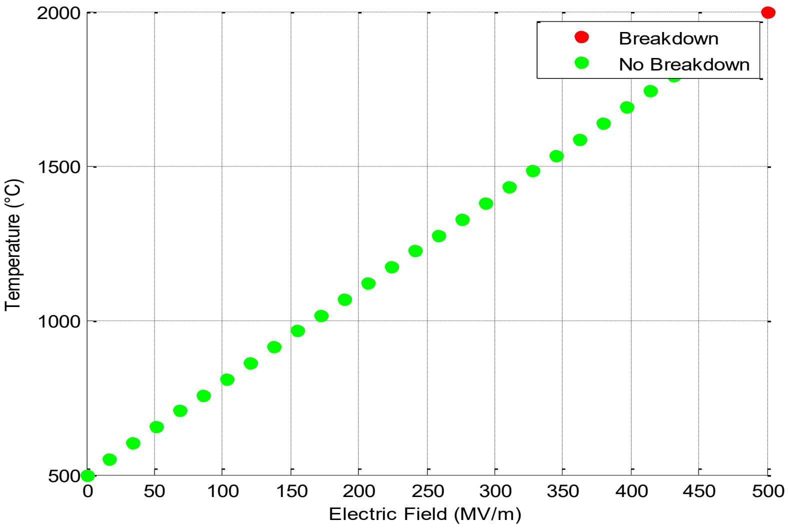

Figure 12: Breakdown Simulation of Composite

Fig. 12 Shows Breakdown Simulation of Composite Intermediate Breakdown Characteristics: The composite material demonstrates intermediate breakdown characteristics between polymer and ceramic. The breakdown electric field increases with temperature, but at a slightly lower rate than that observed in ceramics. Composites reach dielectric breakdown at approximately 500 MV/m, similar to ceramics, though they show a gradual loss in resistivity as temperature continues to rise. This behaviour suggests that composites offer enhanced dielectric strength compared to polymers but still lag behind ceramics in extreme conditions. Effect of Material Composition: The composite's intermediate performance could stem from its combined constituents, likely integrating properties from both polymeric and ceramic-like materials. This structure allows it to benefit from some of the polymer's flexibility and process ability, while also gaining improved dielectric strength and thermal stability from ceramic components. Frequency and Loss Tangent Impacts: Composites exhibit higher loss tangents than ceramics, indicating that frequency can still impact their breakdown behaviour due to increased energy dissipation. This may lead to dielectric heating at high frequencies, making them less suited for extreme high-frequency applications compared to ceramics. However, their stability remains sufficient for moderate frequency and temperature applications, as they maintain a high resistivity up to their breakdown point.

Implications for Material Selection

These findings emphasize the need for context-specific material selection, considering the electrical, thermal, and mechanical requirements of applications. Ceramics are suitable for high-temperature, high-voltage applications, composites for a balanced trade-off, and polymers where flexibility and ease of processing are prioritized.

Further improvements in composite formulations could enhance dielectric strength, potentially surpassing ceramics in performance under certain conditions. Additionally, referencing the breakdown performance in Figures 4, 8, and 12 allows for a clearer understanding of how material modifications impact dielectric reliability in practical applications. These refinements also provide insights into how new material engineering strategies can enhance dielectric properties for future applications.

CONCLUSION

The comparative study of the breakdown strength of polymers, ceramics, and composite dielectric materials has revealed significant insights into their performance under high-voltage and high-frequency conditions. Polymers such as polyethylene (PE) and polyimide (PI) demonstrate excellent flexibility and ease of processing but are limited by their thermal stability. Ceramics, particularly alumina (Al_2O_3) and barium titanate ($BaTiO_2$), exhibit superior breakdown strength and thermal endurance, making them ideal for applications requiring stability under extreme conditions. However, their brittleness presents challenges for mechanical robustness. Composite materials, especially those incorporating nanoscale fillers like silica (SiO_2) and carbon nanotubes (CNTs), strike a balance between enhanced dielectric performance and mechanical resilience, proving to be promising candidates for advanced applications. The findings emphasize that material selection should be context-specific, with careful consideration of the electrical., thermal., and mechanical requirements of the intended application.

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