Turkish Online Journal of Qualitative Inquiry (TOJQI)
Volume 12, Issue 7, July, 2021:1105 – 1111

Analysis of Electrical Properties in ZnO-based Epoxy Nanocomposites

Mihir N. Velani [a], R.R. Patel [b]

[a] Gujarat Technological University, RK. University, Gujarat, mihir.zalawad@gmail.com
[b] G.H. Patel College of Engineering and Technology, Gujarat, r2patel@yahoo.com

Abstract

In recent times, epoxy nanocomposites have been considered as a potential indoor insulation application in power apparatuses due to significantly improved electrical and thermal properties over conventional insulators. The paper discusses the FE analysis of electrical properties of ZnO (zinc-oxide)-based epoxy nanocomposites. The results demonstrate the effect of % volume fraction and frequencies on capacitance, real permittivity, displacement current density, and conduction current density. It has shown the capacitance has changed by 21.36% with a 10% volume fraction at 1000 Hz as compared to the neat epoxy. Besides, the reasons for the advancement in real permittivity and current densities have been discussed.

Keywords: Capacitance, displacement current density, finite element, real permittivity

1. Introduction

The advancement in research and development has led it to design an identical polymeric insulator for specific applications. The epoxy-based nanocomposites have penetrated high-voltage indoor insulation systems due to their superior electrical, mechanical, thermal, and other properties over the conventional glass and ceramic insulators (Ismail, 2018). The inclusion of nanoparticles such as nano clay, Al_2O_3 (alumina), $BaTiO_2$ (barium titanate), BN (boron nitride), MgO (magnesia), SiO_2 (silica), TiO_2 (titania), and ZnO (zinc oxide) to epoxy polymers have demonstrated improved dielectric properties, electric performance and thermal characteristics (Ismail, 2018; Tanaka, 2017). Even though the concept of nanodielectrics is almost three decades mature, the cost involved in the synthesis, characterization, and testing has not been brought down to make it available on a larger commercial platform. Therefore, the epoxy composites have been modeled in a finite element (FE) based-software tool-COMSOL Multiphysics. The tool provides a platform to comprehend the performance of epoxy nanocomposites. The study distinctively shows the importance of FE analysis to reduce prototype and testing costs involved.

The epoxy composites with nano ZnO and other inorganic particles have shown improved electrical and thermal performance. However, no study reports the effects of nanofillers on electrostatic properties. These properties include energy capacity, permittivity, displacement current density, and current density (Singha, 2009; Thipperudrappa, 2020; Tsosons, 2015; Fothergill, 2004). And this has been attempted in the presented study with circular-shaped 60 nm-sized ZnO particles. However, FE-based studies have been reported on the analysis of epoxy nanocomposites with different fillers that reveal the effect of particle concentration (% volume fraction or %wt), size, and shape on various functional properties (Hashim, 2020; Zhong, 2018; Cai, 2017; Kavitha, 2017). The results discuss the effect of % volume fraction and frequencies on capacitances, real permittivity, displacement current density, and conduction current density when subjected to a low-voltage (LV) field application.

2. The FE analysis: Modeling of nanocomposites and boundary conditions

The ZnO-based epoxy nanocomposites have been modeled in an FE based software tool-COMSOL Multiphysics. Figure 1 indicates the modeled neat epoxy of- 1 μm × 1 μm sized and respective boundary conditions.

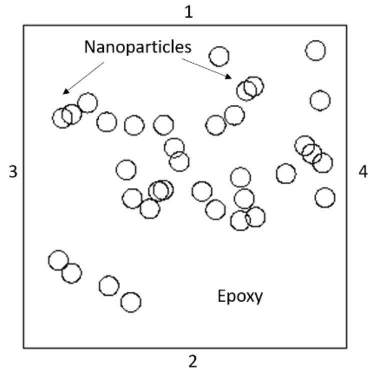

Figure 1. The epoxy matrix with 10 % volume fraction of 60nm-sized particles with boundary conditions

For calculating the real permittivity, the boundary conditions are applied as: side-1 is probed 10 V with the frequency range of 0.01 to 1000 Hz, and side-2 is grounded. The random distribution of particles has been produced with a suitable MATLAB code. Afterward, the circular-shaped 60 nm-sized ZnO particles have been added to the neat epoxy at the filler concentration of 1 to 10 % volume fraction. The particle configurations can be referred to in Table 1.

Table 1. Filler Configuration

Filer concentration (% Volume Fraction)	Circular shaped fillers (nm)		
	15	45	60
1	56	8	3
2	113	16	7
3	169	24	11
4	223	32	14
5	289	40	18
6	339	48	21
7	395	56	25
8	452	64	28
9	508	72	32
10	565	80	35

The modeled composites have been simulated by applying an LVAC electrical field to observe the real permittivity, displacement current density, and current density in the bulk of materials. The properties of materials can be viewed in Table 2.

Table 2. Properties of Materials

Properties	Epoxy	ZnO
Dielectric Constant ε_r	3.5	8.5
Electrical Conductivity S/m	1×10^{-11}	1×10^{-11}
Density kg/m^3	1100	5610
Thermal conductivity W/m. K	0.17	60
Heat Capacity J/kg. K	1250	410

3. Low-voltage frequency analysis

3.1. LV Permittivity test

The permittivity is one of the essential electrical properties to develop robust insulators that can sustain severe operating conditions as it restricts electric fields within. Also, the permittivity decides the ability of an insulator to store electrical energy. The static permittivity is a suitable estimate for alternating fields with low frequencies. As the frequency rises, a quantifiable phase difference- 'δ' arises between the electric field displacement- ‘D’ and applied electric field- ‘E’ (Kasap, 2017). The frequency at which the phase shift turns out to be noticeable varies with temperature [11]. Here, the temperature effects have not been considered. When the dielectric dielectrics are subject to the AC electrical fields, the response of dielectrics is characterized by a complex permittivity. The complex permittivity is given by the empirical formulae (Wadhava, 2007)-

$$\varepsilon_c = \varepsilon' - j\varepsilon'' \qquad (1)$$

where ε_c is the complex permittivity, the real part, ε′, is related to the energy stored in the dielectric and the imaginary part, ε″, is related to various processes that dissipate energy. The imaginary part- ε″ is $\frac{\sigma}{\omega}$ where ‘σ’ is the conductivity and ‘ω’ angular frequency. The simulation results calculate capacitance concerning variable frequencies, and then real permittivity has been derived from equation (2)-

$$\varepsilon' = \frac{C\ d}{\varepsilon_0\ A} \qquad (2)$$

where, C is the capacitance in F, d is the distance between two electrodes, ε_0 is the absolute permittivity, and A is the surface of the electrodes in m2. The complex permittivity has not been derived as straightforward it is not accessible in the FE tool. The simulation results have been presented in terms of capacitance, displacement current density, and current density.

3.1.1. Capacitance and Permittivity

The capacitance of the neat epoxy is 3.09 × 10^{-17} F, and the real permittivity derived from equation (2) is 3.5 that is shown due to brevity. In Figure 2 (a), it is observed that when the epoxy is filled with a 1% volume fraction, the capacitance increases from 3.168773479 × 10^{-17} F to 3.168770667 × 10^{-17} F at 0.01 and 1000 Hz, respectively. In Figure 2 (b), the real permittivity reduces from 3.578917431 to 3.578913561 at 0.01 Hz to 1000 Hz, respectively. The real permittivity starts reducing at increased frequencies (> 1000 Hz) because the net polarization stops influencing. It will be realized when the insulation faces high-frequency overvoltages resulting from switching operations or lightning surges. The material may behave differently due to the influence of surrounding temperature. However, there lies a restriction incorporating temperatures and frequencies in the straightforward FE tool.

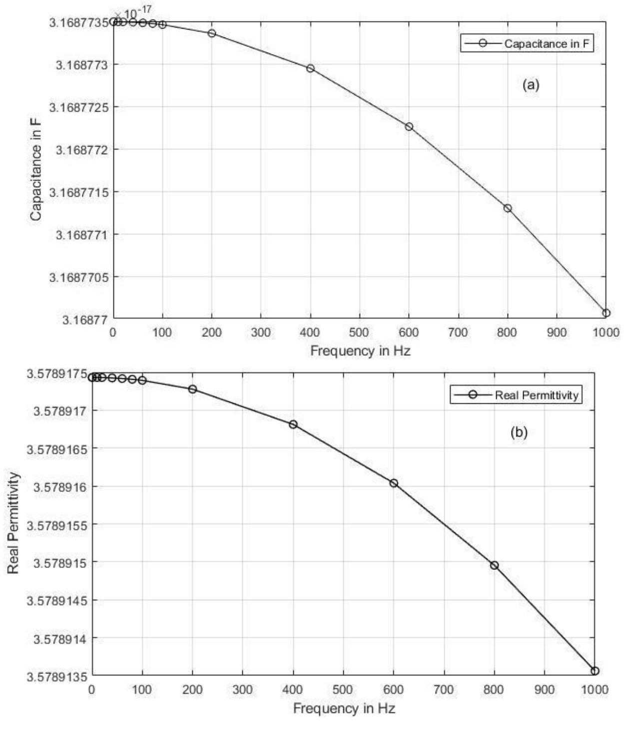

Figure 2. (a) Capacitance and (b) Real Permittivity Vs. Frequency at 1% volume fraction

When the volume fraction is increased to 5%, the capacitance increases from 3.473083 × 10^{-17} to 3.473053652 × 10^{-17} at 0.01 to 1000 Hz respectively. The real permittivity, on the other side, reduces from 3.92261519155994 to 3.92258149075173 at 0.01 to 1000 Hz in order. Patel et al. (Patel, 2012) have reported an experimental-based study on ZnO-based epoxy nanocomposites. Further, when the epoxy matrix is loaded with a 10 % volume fraction, the capacitance and real permittivity amount to 3.75 × 10^{-17} F and real permittivity

4.24. At 1000 Hz, the variation in the capacitance and real permittivity concerning % volume fraction can be observed in Figure. 3. It is worth noting that these changes are very subtle with all volume fractions. However, when it is compared and observed at 1000 Hz with 1-10 % volume fraction, significant changes in capacitance and real permittivity are realized.

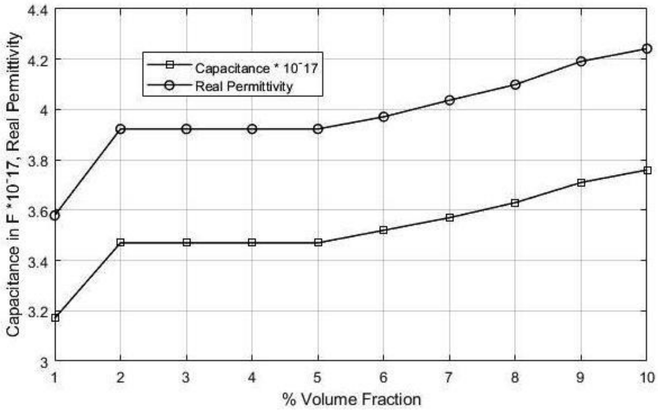

Figure 3. Capacitance and Permittivity Vs. % Volume fraction at 1000 Hz

It is interesting to note that both capacitance and real permittivity show a rising trend with a 1 to 10 % volume fraction. It is attributed to the increased number of particles in the neat epoxy. Further, the real permittivity has increased almost by 1.2 times at the frequency of 1000 Hz, and the same trend is equally applicable for the capacitance.

3.1.2. Displacement Current Density

The displacement current results from changing electric fields with varying frequencies. In contrast, conduction currents result from the flow of free electrons within the bulk of the material, and it requires a medium to flow through.

The importance of the displacement current density is to examine the timely-varying electric field in the material. In Figures 4 (a) and (b), the displacement current density is shown for a 1% volume fraction at the frequency of 0.01 and 1000 Hz, respectively. When the ZnO-based epoxy nanocomposites are filled with a 1% volume fraction, the displacement current density has increased from 6.97×10^{-11} to 0.01 A/m^2 at 0.01 to 1000 Hz, respectively. The increase in the displacement density is attributed to the changing electric fields., i.e., it increases with the increase in frequency.

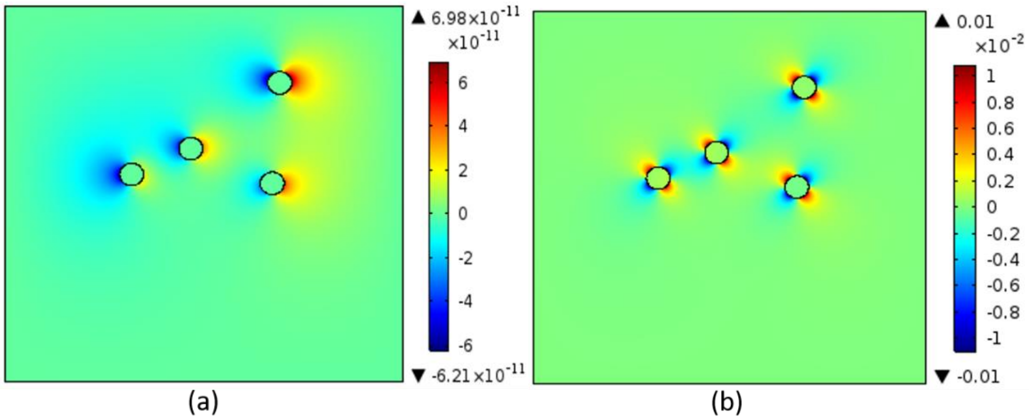

Figure 4. Displacement Current Density in A/m^2 with a 1% volume fraction (a) at 0.01 Hz (b) at 1000 Hz

In Figures 5 (a) and (b), with a 10% volume fraction, at 0.01 and 1000 Hz, the displacement current density is respectively 3.57×10^{-11} A/m^2 and 0.08 A/m^2 correspondingly. It is imperative to note that the displacement current density is maximum when the particle distances are smaller than particle sizes at lower frequencies and vice-versa. It is inferred from the characteristics that the real permittivity plays a crucial role in the dynamics. Thus, it is predicted that at lower permittivity, the interfacial region is less stressed, Kavitha et al. (Kavitha, 2017) have reported a similar study for a specific application.

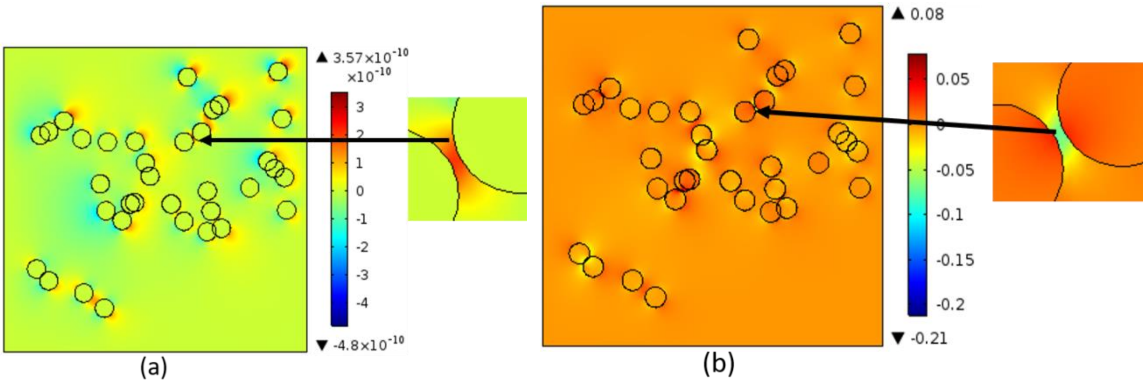

Figure 5. Displacement Current Density in A/m^2 (a) at 0.01 Hz (b) 1000 Hz with a 10% volume fraction

In Figure 6, the displacement current density exhibits a rising trend concerning 1, 5, and 10 % volume fraction within the frequency range. It implies the relative shift of positive and negative electric charges becomes significant, which leads to the rise in electric polarization and field. As a result, the dielectric losses may lead to the electrical breakdown of the material.

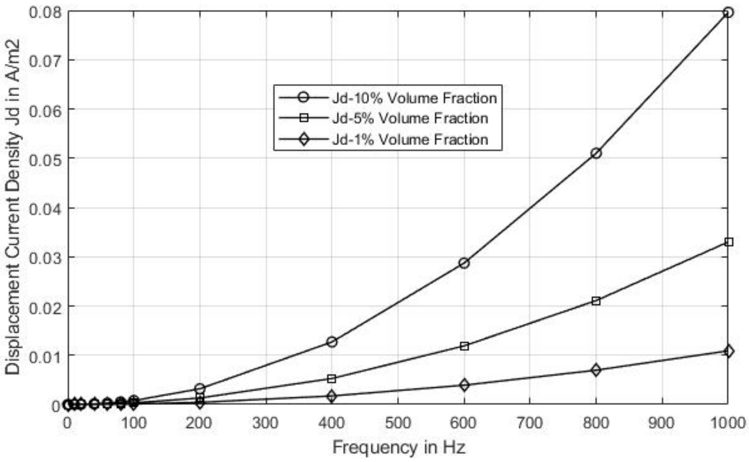

Figure 6. Displacement Current Density in A/m^2 (a) at 0.01 Hz (b) 1000 Hz with a 10% volume fraction

3.1.3. Current Density

The conduction currents result from the movement of free electrons. The purpose of analyzing the current density concerning is to examine the change of electrical conductivity. At higher frequencies, the conducting region within the bulk of material narrows down, which intensifies the current density. Moreover, the rate of flow of electrons tends to be higher within the interparticle regions. The higher magnitudes of the conduction current are not favorable for dielectric as they gradually lead to thermal breakdown. With 1% volume fraction, the current density increases from 2.09×10^{-4} A/m^2 to 4 A/m^2 at the frequency of 0.01 to 1000 Hz, correspondingly. Further, when the volume fraction is increased to 5 and 10%, the current density surges to 17.83 A/m^2 and 21.6 A/m^2 at 1000 Hz, respectively. In Figures 7 (a) and (b), at a 10% volume fraction, the current density is illustrated at 0.01 and 1000 Hz, respectively. It is interesting to note that the current density is extreme in the interparticle region. It is because as the distances among the particles shrink than the particle sizes. It is viewed in the zoomed inset of Figure. 7 (b).

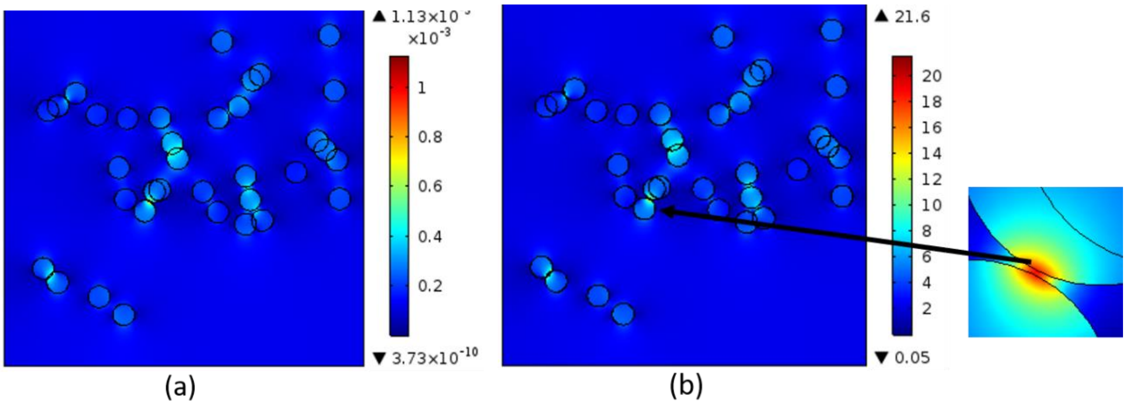

Figure 7. Current Density in A/m^2 with a 1% volume fraction (a) at 0.01 Hz and (b) 1000 Hz

The current density is independent of the permittivity. Further, in other parts of the epoxy matrix, it is minimum due to its low electrical conductivity. Figure 8 displays the relationship between the current density and frequencies, and it is inferred that the current density increases with % volume fraction and frequency.

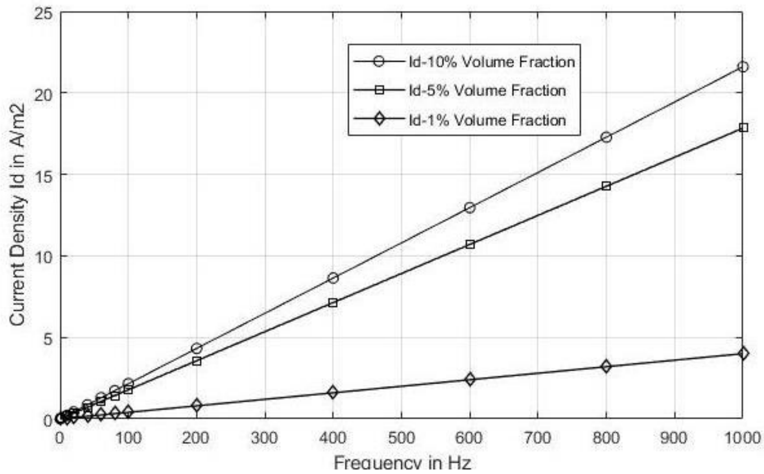

Figure 8. Current Density (A/m^2) Vs. Frequecies with 1, 5, and 10% volume fraction

4. Conclusions

In the study, the ZnO-based nanocomposites have been analyzed by employing the FE technique. The capacitance, real permittivity, displacement current density, and conduction current density have been analyzed from the simulated tests. The below points are imperative to deduce here:

1. At high frequency, the storage capacity and real permittivity have increased with the % volume fractions.

2. Besides, the real permittivity has exhibited a declined trend with an increase in frequency.

3. The displacement current density has increased nearly 7.3 times with a 10% volume fraction than a 1% volume fraction at 1000 Hz. Similarly, the current density has surged to about 5.4 times.

4. It is suggested that with these analyzed properties, the % volume fraction is to be optimized to limit the electric fields.

The presented study is progressive to acquire the optimum blend of the electrical and thermal properties.

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