Experimental Study for Effects of Cost-Fewer Nanoparticles on Dielectric Performance of Polypropylene Nanocomposites

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***Abstract*—In this study, the enhancement of dielectric characterization has been investigated on Polypropylene (PP) as matrix that highly modified by presence of costless nanofillers clay and fumed silica. And so, dielectric strength of nanocomposites has been improved significantly with respect to unfilled materials under high voltage alternating current (HVAC) electric fields. Filling nanoparticles into polymers provide advantages over unfilled polymers because they increasing resistance to degradation according to their types and concentrations. Therefore, an experimental work for dielectric loss and capacitance of the new polypropylene nanocomposite materials have been investigated and compared with unfilled polypropylene industrial materials. A simplified HVAC breakdown model test has been used for experimental tests and measurements; whatever, the rate of dielectric strength of tested nanocomposite materials precedes the conventional polypropylene insulation materials under AC electric fields. Therefore, the dielectric strength is measured for several new polypropylene nanocomposite specimens. These experimental measurements depict that the incorporation of clay or fumed silica nanoparticles into Polypropylene (PP) has been controlled the dielectric strength and voltage endurance significantly compared to conventional materials with respect to their types and concentrations. Finally, a thermal effect on suggested nanocomposites under uniform and non-uniform electric fields has been analyzed that encourage industrial fabrication production for the suggested cost-fewer nanoparticles.**

***Index Terms*—dielectric strength, nanocomposite, nanoparticles, polypropylene, insulation**

I. Introduction

The insulation strength of discharge gaps is one of the main factors determining the reliability of HV devices. Also, increasing demand for high performance of polymers requires that the dielectric strength of the polymers be measured accurately of their intended use. Lack of accurate data on dielectric strength leads to design short comings; either use of excessive insulation resulting in more expensive equipment's or on the other hand, use of inadequate insulation with increased risk of premature failure. The safe operation of high voltage electrical energy transmission grids depends on the reliability of its components, as switchgears, power transformers and gas insulating lines. Their reliability depends primarily on the performance of the insulating structures they contain. Nanoparticle-filled polymers provide advantages over micron-filled polymers because they provide resistance to degradation, and improvement in thermo-mechanical properties without causing a reduction in dielectric strength [1]-[8]. In most papers devoted to the research of polymeric dielectric behavior of polymeric nanocomposites which have gained importance in the manufacture of products of high performance properties like light weight, material transparency, enhanced stiffness and toughness, increased barrier properties, decreased thermal expansion, decreased flammability and increase in dielectric properties for different industries such as automobiles, electrical and electronics, packaging, coatings etc. Polymer nanocomposites are composite materials having several wt% of inorganic particles of nanometer dimensions homogeneously dispersed into their polymer matrix. This new type of polymer composite has recently drawn considerable attention because nanocomposites or nanostructured polymers have the potential of improving the electrical, mechanical, and thermal properties as compared to the neat polymers [9]-[16].

The use of nano-additives in dielectric materials has made great progress in the last few years. Many papers discussing the general overview, theory and the functionality of nanocomposite dielectrics have been published. Nano-silica has mostly been used in industrial polymer matrices. Earlier research results regarding Nano-particles which used for purposes of insulation mostly deal with various industrial polymers. The nanostructured polymeric materials are objects of great interest to researchers. It is due to the fact that nanofillers provide improved surface area and enhanced thermal and electrical properties. The present work addresses the analysis of dielectric and thermal properties of standard enamel and Zirconia mixed enamel [17]-[20]. For equipment typified by a transformer or gas insulated switchgear (GIS), the dielectric BD of an insulation element and the voltage-time characteristic (V-t characteristic) can be well approximated with the inverse-n-power rule [21]:

$$V^n t = K \qquad (1)$$

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where *K* is a constant, *t* stands for a time-to-BD at a given voltage of *V*.

And so, the cumulative fault probability P generally conforms to the Weibull distribution and it can be expressed as [22]-[24]:

$$P = 1 - exp(-AV^m\ t^a) \quad (2)$$

where A is a constant, "a" is a time shape parameter, and "m" is a voltage shape parameter. The a- and m-values effect increasing movements of P and the A-value is concerned with a scale i.e. such as a point of taking P = 50% etc. The current research has been focused on the electric breakdown failure of Polypropylene (PP) with various added cost-fewer clay and fumed silica nanoparticles.

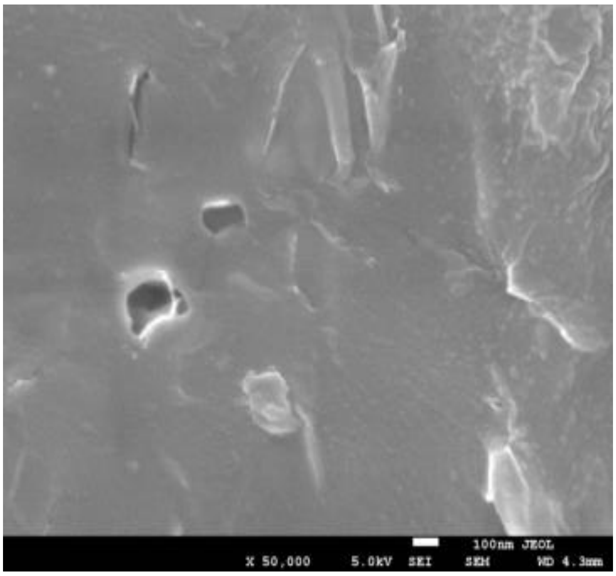
II. Experimental Setup

Nanoparticles: Spherical nanoparticles shape (Dia.: 10nm) have been used in our research and in the most polymer applications. Cost less of clay catalyst is the best filler among nanofillers industrial materials. On the other wise, nanoparticles of fumed silica are fluffy white powders with an extremely low density, marketed. And so, fumed silica powders used in paints, coatings, silicone sealants, adhesives, cable compounds and gels, and plant protection.

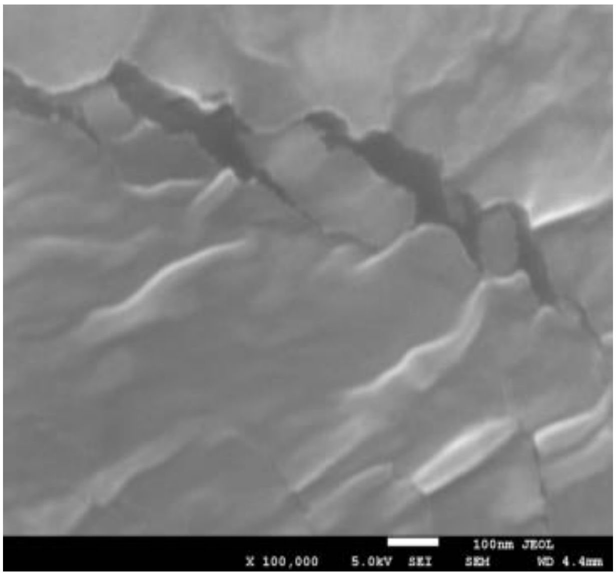
Polypropylene: Polypropylene is one of the most common and versatile thermoplastics in the plastics industry. Filling polypropylene with a certain nanoparticles greatly increases electrical, dielectrically, and mechanical properties, tensile strength, impact strength, flexural modulus, and deflection temperature under load with a corresponding reduction in elongation according to type and percentages of nanofillers.

PP Nanocomposites: Additives of clay and fumed silica nanoparticles to the base Polypropylene industrial polymers has been fabricated by using mixing, ultrasonic, and heating processes in nanotechnology Research Centre, Aswan University - Egypt. Preparation of studied polymers has been used SOL-GEL method [25]. Filling polypropylene with a certain nanoparticles greatly increases electrical properties, tensile strength, impact strength, flexural modulus, and deflection temperature under load with a corresponding reduction in elongation according to type and percentages of nanofillers. Thus, SEM images illustrate penetration of nanoparticles in polypropylene for Clay/PP nanocomposite and Fumed silica/PP nanocomposite as shown in Fig. 1. The base of Polypropylene materials is a commercially available which industrial products are already in use in the manufacturing of high-voltage (HV) and their properties detailed in Table I. HIOKI 3522-50 LCR Hi-tester device is measuring characterization of nanocomposite insulation industrial materials.

HIOKI 3522-50 LCR Hi-tester device has been measured electrical parameters of nano-metric solid dielectric insulation specimens at various frequencies: |Z|, |Y|, θ, Rp (DCR), Rs (ESR, DCR), G, X, B, Cp, Cs, Lp, Ls, D (tan δ), and Q. Specification of LCR is Power supply: 100, 120, 220 or 240V (±10%) AC (selectable), 50/60Hz, and Frequency: DC, 1mHz to 100kHz, Display Screen: LCD with backlight / 99999 (full 5 digits), Basic Accuracy: Z: ±0.08% rdg. Θ: ±0.05°, and External DC bias ± 40V max. (option) (3522-50 used alone ±10V max./using 9268 ± 40 V max.). Fig. 2 shows HIOKI 3522-50 LCR Hi-tester device for measuring characterization of nanocomposite insulation industrial materials.



(a) Clay/PP nanocomposite



(b) Fumed silica/PP nanocomposite

Figure 1. SEM images for polyethylene nanocomposites

TABLE I. Dielectric Properties of Pure and Nanocomposite Insulation Materials

Materials	Dielectric Constant AT 1KHZ	Resistivity (Ω.m)
PP + 0%wt Clay	2.28	10^{8}
PP + 1%wt Clay	2.21	10^{9}
PP + 5%wt Clay	1.97	10^{9}-10^{10}
PP + 10%wt Clay	1.75	10^{10}-10^{12}
PP + 1%wt Fumed Silica	2.29	10^{7}
PP + 5%wt Fumed Silica	2.37	10^{7}-10^{5}
PP + 10%wt Fumed Silica	2.47	10^{5}-10^{4}

Figure 2. HIOKI 3522-50 LCR Hi-tester device

Polymer nanocomposites are characterized by an enormously large interfacial surface area between the nanoparticles and the polymer matrix into which they are embedded. Fig. 3 illustrates Hi-pot Tester Model ZC2674 device for experiment uniform and non-uniform electric field distribution through the thickness of insulation layer with different nanocomposite materials.

Figure 3. HIPOT tester model ZC2674 device

III. Measurement Configuration

The applied AC voltage on the specimen was varied from 0kV until breakdown occurs, whatever, AC conduction current was measured through testing the specimen. Experimental results for AC uniform and non-uniform electric fields have been investigated for studying the effect of nanoparticles on industrial insulation materials. Experimental results are focused on Polypropylene, with various percentage weights of nanoparticles. Configuration of both two electrodes of uniform electric field has been made from copper and has 35mm Diameter but configuration of tip electrode of non-uniform electric field has 0.5mm diameter.

IV. Effect of Nanoparticles on Polypropylene Characterization

Fig. 4 shows loss tangent as a function of frequency for Clay/PP nanocomposites at room temperature 25 ℃. It is obvious that the loss tangent of Clay/PP nanocomposites decreases with increasing frequency but it increases with increasing clay percentage nanofillers, especially at high frequencies. Fig. 5 shows capacitance as a function of frequency for Clay/PP nanocomposites. The measured capacitance increases with increasing percentage of clay nanofillers in the nanocomposite. But, the capacitance of Clay/PP nanocomposites decreases with increasing frequency. Fig. 6 shows loss tangent as a function of frequency for Fumed Silica/PP nanocomposites at room temperature 25 ℃. The measured loss tangent of Fumed Silica/PP nanocomposites decreases with increasing frequency but it increases with increasing Fumed Silica percentage nanofillers up to 5%wt, but it is fall down rate from 5%wt up to10%wt.

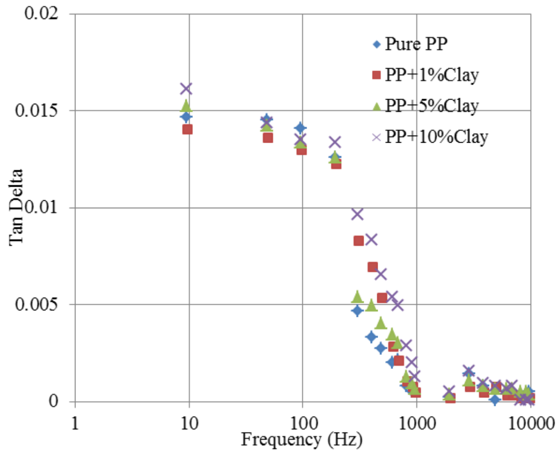


Figure 4. Effect of clay nanoparticles on loss tangent of polypropylene at room temperature 25 ℃

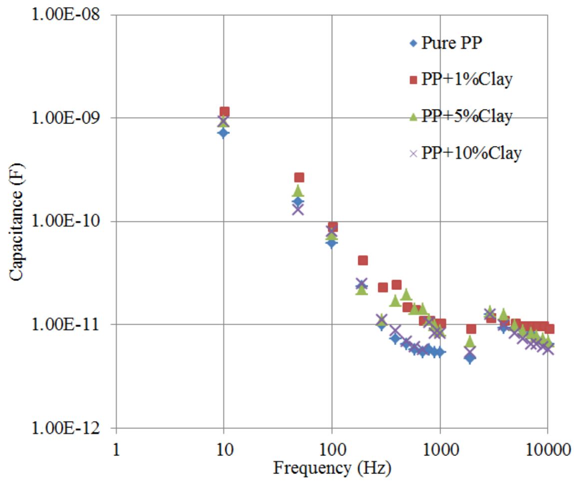


Figure 5. Effect of clay nanoparticles on capacitance of Polypropylene at room temperature 25 ℃

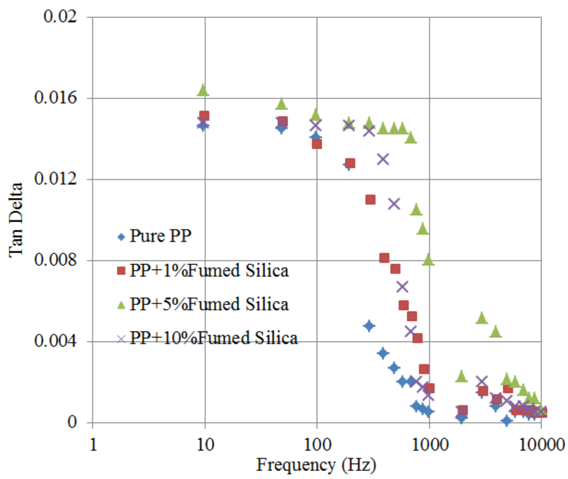


Figure 6. Effect of fumed silica nanoparticles on loss tangent of polypropylene at room temperature 25 ℃

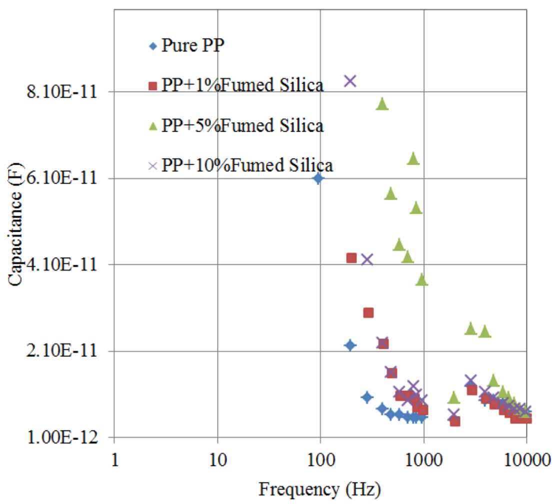


Figure 7. Effect of fumed silica nanoparticles on capacitance of polypropylene at room temperature 25 ℃

Fig. 7 shows capacitance as a function of frequency for Fumed Silica/PP nanocomposites at room temperature 25 ℃. Also, this figure contrasts the measured capacitance with rising percentage of Fumed Silica nanofillers in the nanocomposite. It is cleared that, the capacitance of Fumed Silica/PP nanocomposites decreases with increasing frequency but it increases with increasing Fumed Silica percentage nanofillers up to 5%wt, but it down rate from 5%wt up to 10%wt. From the above results, it is obvious that, the importance of nanoparticles appears in changing the dielectric properties of polymers that accept gained power for manufacture products of high voltage applications. Therefore, polypropylene dielectric characterization measurements indicate the capability of insulating materials in high voltage industrial applications.

V. Effect of Uniform Electric Fields on Polypropylene Nanocomposites

Fig. 8 shows effect of adding clay nanoparticles on dielectric strength and leakage pass current in Polypropylene materials in uniform electric field. It has been cleared that, increasing percentage of clay nanoparticles in the nanocomposite increases dielectric strength of the industrial materials. Also, dielectric strength of the new nanocomposite materials has increased by increasing percentage of clay nanofillers up to 10%wt. but leakage pass current has decreased specially with adding clay nanoparticles percentages. Fig. 9 shows effect of adding fumed silica nanoparticles on dielectric strength and leakage pass current in Polypropylene materials in uniform electric field. It has been cleared that, increasing percentage of fumed silica nanoparticles up to 10%wt. in Polypropylene increases leakage pass current through the new nanocomposite industrial materials but decreases dielectric strength of Polypropylene industrial material. And so, it is noticed that, dielectric strength of nanocomposite materials decreases with increasing percentage of fumed silica nanoparticles gradually up to 10% in Polypropylene.

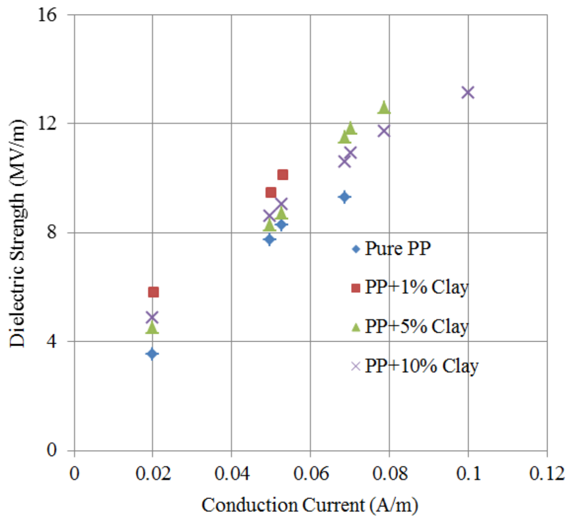


Figure 8. Effect of clay nanoparticles on Polypropylene under uniform electric field

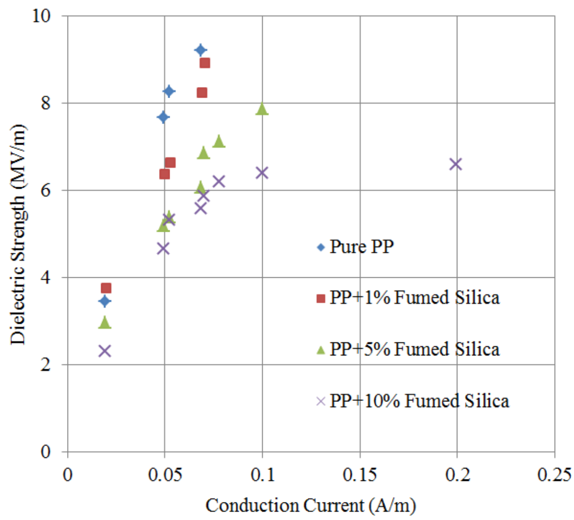


Figure 9. Effect of fumed silica nanoparticles on Polypropylene under uniform electric field

VI. Effect of Non-Uniform Electric Fields on Polypropylene Nanocomposites

Fig. 10 shows effect of adding clay nanoparticles on dielectric strength and leakage pass current in Polypropylene materials in non-uniform electric field. This Figure illustrates that increasing percentage of clay nanoparticles in the nanocomposite increases dielectric strength of the industrial materials. However, leakages pass current decreases with increasing clay nanoparticles percentages. Fig. 11 shows effect of adding fumed silica nanoparticles on dielectric strength and leakage pass current in Polypropylene materials in non-uniform electric field. It has been illustrated increasing percentage of fumed silica nanoparticles up to10%wt. in Polypropylene increases leakage pass current through the new nanocomposite industrial materials but decreases dielectric strength of Polypropylene industrial material with increasing percentage of fumed silica nanoparticles gradually up to 10% in Polypropylene.

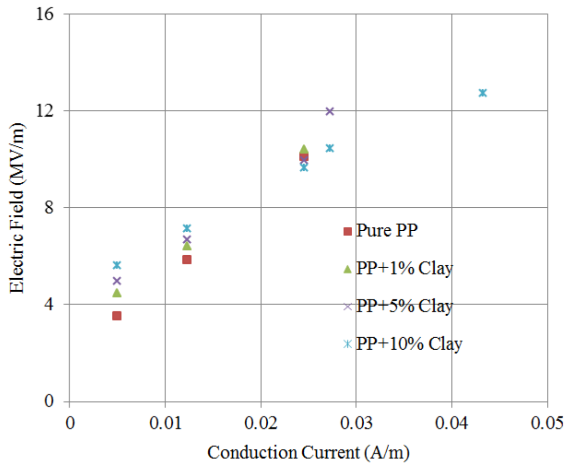


Figure 10. Effect of clay nanoparticles on Polypropylene under non-uniform electric field

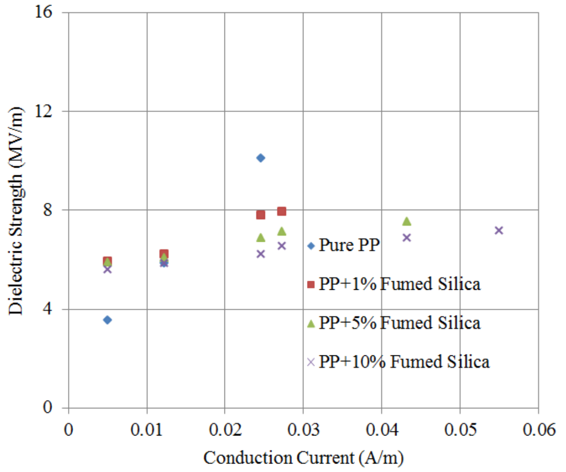


Figure 11. Effect of fumed silica nanoparticles on Polypropylene under non-uniform electric field

VII. Thermal Effect of Nanoparticles under Uniform and Non-Uniform Electric Fields

TABLE II. Maximum Dielectric Strength of Pure and Nano-Composite Materials

Materials	**Dielectric strength (MV/m) at (20 ℃)**	**Dielectric strength (MV/m) at (60 ℃)**
Uniform Electric Field		
Pure PP	9.1953	6.7693
PP + 10%wt Clay	13.1628	12.3452
PP + 10%wt Fumed Silica	4.7854	3.1673
Non-uniform Electric Field		
Pure PP	10.1107	8.5693
PP + 10%wt Clay	12.7233	10.7458
PP + 10%wt Fumed Silica	7.1546	5.3673

Table II depicts dielectric strength of pure and nano-composite materials (Clay/Polypropylene, and Clay/Polypropylene) in uniform electric field with varying cell test temperature from room temperature at 20 ℃ to 60 ℃. It is cleared that, in uniform and non-uniform electric fields, increasing thermal temperature decreases the dielectric strength of nanocomposite, whatever; the rate of reduction in dielectric strength of polypropylene nanocomposites is lower than reduction rate in dielectric strength of pure polypropylene. Also, Dielectric strength of pure and nanocomposite materials in non-uniform electric field is higher than dielectric strength of pure and nanocomposite materials in uniform electric field and so, reduction rate in dielectric strength of pure industrial materials is higher than that happened in nanocomposites with increasing cell test temperature.

VIII. Conclusions

Adding clay nanoparticles to polypropylene industrial materials decreases leakage pass current smoothly through the new nanocomposite industrial materials and so, the new nanocomposite withstand more applied electric field strength according to weight percentage of clay nanofillers and polymer molecular type. Increasing percentage clay and fumed silica nanoparticles up to limited certains increases the loss tangent and capacitance of Polypropylene nanocomposites.

Adding fumed silica nanoparticles to Polypropylene industrial materials increases capacitive leakage pass current through the new nanocomposite industrial materials but, the new nanocomposites withstand low applied electric field strength according to percentage of fumed silica nanofillers and polymer molecular type.

Rate of reduction in dielectric strength of polypropylene nanocomposites is lower than reduction rate in dielectric strength of pure polypropylene with raising thermal conditions under uniform and non-uniform electric fields.

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