



## High Voltage Cross-Linked Polyethylene Insulator Characteristics Improvement Using Functionalized ZnO Nanoparticles



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### Abstract

This study aims to develop large-scale commercial Cross-Linked Polyethylene (XLPE) nanocomposites used for industrial applications with power cables insulations. To achieve this goal, XLPE/zinc oxide nanocomposites were prepared with four unique loadings of Zinc Oxide (ZnO) nanoparticles: 0.5, 2, 3.5 and 5 wt.%, in the presence of appropriate coupling agent which used to reduce the agglomeration of nanoparticles and to improve the compatibility inside the polymer matrix. Amino silane was the coupling agent used in this study and the nanocomposites preparation was done using the melt blending method. The morphology and the distribution of nanoparticles inside XLPE polymer were studied using Field Emission Scanning Electron Microscopy (FE-SEM). The mechanical properties were also evaluated. Using Differential Scanning Calorimetry (DSC) and Thermo Gravimetric Analysis (TGA), the thermal properties for nanocomposites were investigated. The dielectric properties of these prepared XLPE/ZnO nanocomposites were studied by measuring the loss tangent ( $\tan \delta$ ) and the dielectric constant ( $\epsilon_r$ ) under frequencies ranging from 1 Hz to 1 MHz. The AC Breakdown Voltage (AC-BDV) was also measured using a controlled high voltage testing transformer (50 Hz) under the sphere-to-sphere field then; the AC dielectric strength was calculated using the Finite Element Method (FEM) technique.

**Keywords:** XLPE, Nanocomposites, Zinc oxide nanoparticles, Electrical, Thermal, and Mechanical properties

### 1. Introduction

The reliability, availability, easy fabrications, appropriate processing ability, low cost, and excellent electrical insulation properties of polymers bolster their using for high voltage cables insulation in a wide range [1]. The most common types in electrical insulating materials of cables in large-scale are Polyethylene (PE) and Polyvinyl Chloride (PVC). These polymeric materials are rigid strong thermoplastic, and have excellent dielectric and mechanical properties. Thus polymeric materials are used in a lot of applications such as high-voltage (HV) electrical insulation, switchgear spacer insulations,

capacitor insulation, etc. [2, 3]. Cross-linked polyethylene (XLPE) is an important form of polyethylene and XLPE cables constitute about 2 - 5% of installed high voltage (HV) cable capacity in the 115-161 kV range and make up about 50 - 70% of new cable installations in the HV range (220 kV and more). During normal operation, it is found that, the underground power cables performance is affected by environmental conditions because it is subjected to various kinds of stresses, heat, and humidity which will result in insulation deterioration. This degradation changes the chemical and physical properties of the XLPE cable and results in generating a leakage current inside the insulators. This leakage current is directly proportional to the aging degree of the cable

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insulation. Besides; it will endanger the personal safety and this will render the use of polymeric materials [4, 5]. To solve this problem, inorganic particles can be incorporated within the polymer insulator material to produce what is called polymer composites. Generally, composite material means a combination of two or more constituents that have significantly distinct chemical and physical properties [6]. Recently, there are a lot of studies that interested in the development of these materials using the concept of the composite to enhance their properties and increase the lifetime and reliability of these insulators [7-16]. Clearly; the properties of polymer composites may be improved by incorporating inorganic micro fillers but their mechanical performance and electrical properties still need to be improved. This can be done by introducing another generation of dielectrics called nanodielectrics or polymer nanocomposites (PNC) [17, 18]. Polymer nanocomposites (PNC) are composite materials with inorganic particles with a dimension of a nanometer (not exceed 100 nm). It must be distributed homogeneously inside the polymer matrix [19]. In many studies it was seen that, the conventional micro filled materials sometimes reduce the dielectric strength of insulation polymer and that is may be due to bulk charge accumulation [18]. Moreover, the nanofiller materials lead to presence of large interfacial areas "an interaction zone between the polymer matrix" and filler. So, the particle type, size, surface, and weight of the nanoparticle inside the polymer nanocomposites play an important role in its beneficial properties [20, 21] To achieve these novel properties, the nanoparticles dispersion inside polymer matrices must be enhanced and that is may be done by the chemical method which uses silane coupling agents or compatibilizers to improve the interfacial adhesion between the polymer and the filler. This functionalization process of nanoparticle surfaces will result in changing the chemistry of nanoparticles to be compatible with that of polymers and to eliminate the agglomeration within the polymer matrix significantly [22-25]. In power industry field, the most popular inorganic filler nanoparticles have been used in enhancing the performance of insulating polymeric materials are clay, acrylic (PA40), silica (silicon dioxide) ( $\text{SiO}_2$ ), alumina ( $\text{Al}_2\text{O}_3$ ), titanium dioxide ( $\text{TiO}_2$ ), particularly aluminum nitride (AlN) boron nitride (BN), silicon carbide (SiC) and other metal

oxides like magnesium oxide ( $\text{MgO}$ ), zinc oxide ( $\text{ZnO}$ ), etc [26]. These fillers are often incorporated into electrical insulating polymers to achieve good electrical, mechanical, and thermal properties. In recent year's zinc oxide has promoted itself as an interesting metal oxide material because of its unique physical and chemical properties such as high chemical and mechanical stability, a broad range of radiation absorption, high catalysis activity, electrochemical coupling coefficient, nontoxic nature, etc. [27, 28]. Additionally, zinc oxide is considered as a semiconductor with a broad energy band of 3.37 eV and high band energy of 60meV [29-30]. This study aims to discuss the effect of incorporating nonfunctionalized and functionalized ZnO inside the XLPE matrix using an industrial method. The size of the nanoparticles will be measured. The mechanical characteristics and the dielectric properties such as relative permittivity, loss tangent and dielectric strength will be measured.

## 2. Experimental setup

### 2.1. Material

CLNA-8141EHV is a crosslinked low-density polyethylene (XLPE) compound designed for insulation of high voltage power cable with a high degree of cleanliness was provided by El- Sewed Electric Co., Egypt. Methane sulfonic acid with 98 % purity was purchased from LOBA Chemie. The coupling agent used is Gamma-amino propyltriethoxy silane abbreviated as "amino silane" has a purity 99% which was purchased from Momentive Inc.

### 2.2. Preparation Zinc Oxide (ZnO) Nanoparticles

Typical 1.314 g zinc acetate and 0.48 g NaOH were dissolved in 330 ml ethanol and refluxed at 60 °C for one hour. After the reaction was complete, de-ionized water was added and the resulting white solid products separated from the dispersion supernatant by centrifugation at 7000 rpm for 5 min repeatedly then dried in an electrical oven at 60°C [31].

### 2.3. Modification of Zinc Oxide (ZnO) Nanoparticles

The surface modification of nanoparticles was performed through two sequential steps.

In the first step, 10 g of ZnO were stirred with 100 ml of 10% methane-sulfonic acid at 110 °C for 4 hours. After that, the powder was collected by centrifugation at 1500 rpm for 5 min and washed many times with de-ionized water before drying in a vacuum oven at 120 °C for 24 hours. In the second step, in a round flask 3 g of the activated ZnO nanoparticles is added to 60 ml of toluene and sonicated in water bath sonicator (Elmasonic, S-60H) for 30 min at 70 °C followed by stirring for 2 h at 500 rpm and 70 °C. A solution of 10% (wt/wt) of amino silane in toluene was added dropwise with continuity of the stirring process for 8 hours. Finally, the functionalized nanoparticles were collected and washed with isopropanol and dried for 24 hours in a vacuum oven at 120 °C for further characterization [32-33].

#### 2.4. Preparation of XLPE/ZnO Nanocomposites

In this study, the melt blending method which is the master batch method in the El-Sewedy Egy-tech. Each nanocomposite sample consists of 150 g of XLPE pellets with different weights of either functionalized or nonfunctionalized ZnO nanoparticles. XLPE/ZnO sheets, with dimension 20×20 cm and 1.7 – 2.3 mm thicknesses were prepared as following; the mixture was blended in the two-roll mixer (Battaglion, MCC 150\*300/R-o) at 150 °C for 15 min, with 30 rpm. Finally, the samples were pressed at 160 °C under 200 bars for 20 min using GDB-Laboratory hot/cold press (Gibitre instruments Co.) followed by boiling in water for 3-4 hours and left to cool down slowly.

### 3. Characterizations

#### 3.1. Morphology studies

The size of ZnO nanoparticles was analyzed using high-resolution Transmission Electron Microscope (TEM) with a model type (JEOL-JEM-2100), and the images have been taken at an acceleration voltage of 120 kV. The surface morphology of XLPE/ZnO nanocomposites has been studied using Field Emission Scanning Electron Microscopy (FE-SEM) (Quanta FEG 250, FEI-Inc.). The microscope is attached to the energy dispersive X-ray analysis (EDX) unit, and the images were obtained with an accelerating voltage of 10–15 kV.

#### 3.2. Thermogravimetric analysis (TGA)

The thermal stability for XLPE/ZnO nanocomposites has been studied by thermogravimetric analysis (TGA, Shimadzu DTG-60, Japan) using an STA 6000 Perkin

Elmer Analyzer from 25 °C to 900 °C at a heating rate of 10 °C/min under argon.

#### 3.3. Differential Scanning Calorimetry (DSC)

Differential Scanning Calorimetry (DSC) analysis was used to observe the changes in XLPE/ZnO nanocomposites exposed to a series of heating cycles. Thermal characteristics were investigated using Shimadzu DSC-60 differential scanning calorimeter Columbia, EUA computer data system. Specimens were heated with a scan rate of 10°C/min with a temperature range from 60 to 110°C in a nitrogen atmosphere.

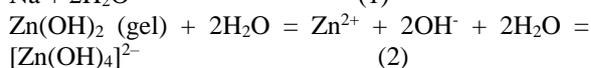
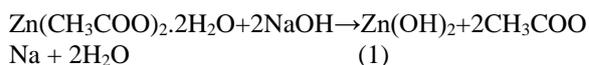
#### 3.4. Dielectric properties

The dielectric properties are characterized by the loss factor, the dielectric strength, and the relative permittivity. The determination of the breakdown strength was carried out using a sphere-to-sphere test cell energized from a test transformer (400V/250kV). The test cell is filled with transformer oil according to ASTM (D149-09) standard. The breakdown strength for all samples has been measured. The measuring setup was modeled using a finite element method and the distribution of voltages and electric fields were determined in and around the different insulating samples.

### 4. Results and discussions

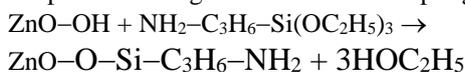
Zinc oxide (ZnO) nanoparticles were prepared by low-temperature chemical growth method through the reaction of zinc acetate with NaOH. The mechanism of this process is a complex and mostly includes two main steps: first the generation of a ZnO nuclei, and subsequent ZnO crystal growth.

Zinc acetate reacts with NaOH giving colloid Zn(OH)<sub>2</sub> (Eq. 1). Apart of the colloids Zn(OH)<sub>2</sub> dissolves into Zn<sup>2+</sup> and OH<sup>-</sup> (Eq. 2). When the concentration of Zn<sup>2+</sup> and OH<sup>-</sup> reaches the supersaturation degree of ZnO, ZnO nuclei will form (Eq. 4). So, the complex (Zn(OH)<sub>4</sub><sup>2-</sup>) serves as basic growth units for the preparation of ZnO nanostructures [34].



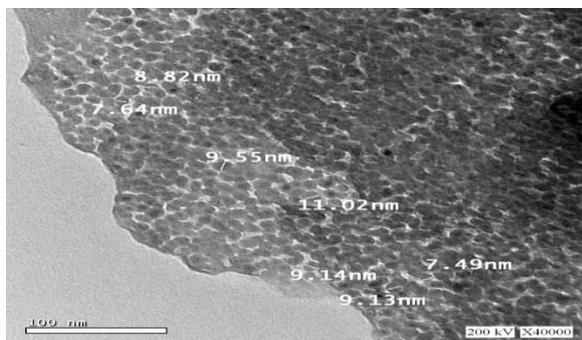


Since the surface functionalization is the most common way to reduce the surface energy of nanoparticles consequently improve their compatibility with polymer matrix. So, the functionalization of ZnO nanoparticles was performed by using amino silane as a coupling agent to enhance the dispersion of ZnO within the polymeric matrix so, amino silane was used. This will, in turn, affect the morphology structure and electrical properties of the obtained nanocomposites. The functionalization of nanoparticles was performed through two sequential steps. Activation of ZnO surface, through the acid etching way, to increase the surface concentration of hydroxyl groups. Followed by surface modification of the particles using amino silane as coupling agent.



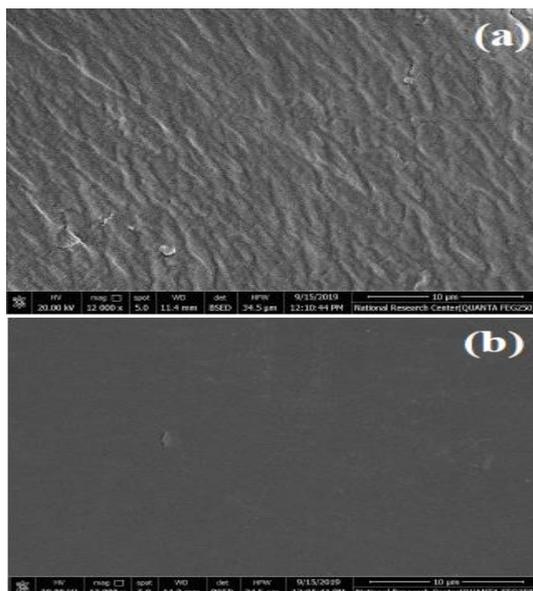
#### 4.1. Morphological Analyses

Electron microscopy is an excellent tool to characterize the morphology of the prepared ZnO nanoparticles. According to TEM results as shown in Fig. 1 ZnO nanoparticles was spherical with average size 7–11 nm.



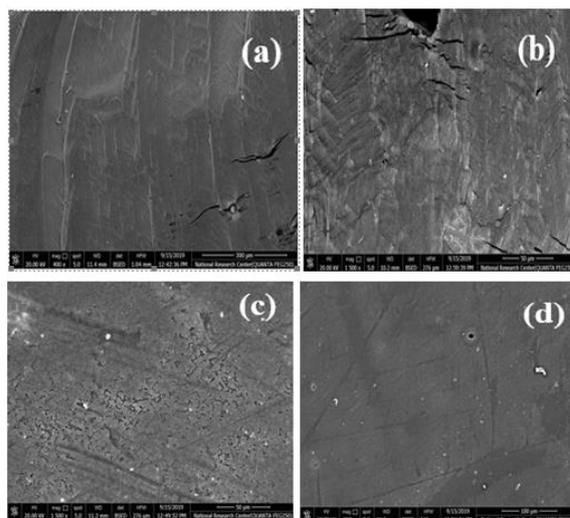
**Fig. 1.** TEM micrographs of ZnO nanoparticles

The scanning electron microscope was employed to analyze the structure of the prepared XLPE without nanoparticles and the dispersion of ZnO nanoparticles into polymer matrix. The SEM images indicated plate like shape and uniform surface, Fig.2a & 2b.



**Fig. 2.** SEM micrographs of; Cross-section area (a) and surface (b) of the XLPE without nanoparticles

By embedding the nonfunctionalized and amino silane functionalized ZnO onto XLPE, the surface morphology of composite was affected (Fig. 3). The good dispersion without a formation of agglomeration can be observed with functionalized ZnO/XLPE composite within cross-section area and surface (Fig. 3 b, d). While the nonfunctionalized ZnO/XLPE composite, aggregates of ZnO appeared as white dots within cross-section area and surface (Fig. 3 a, c), the white light region is the filler in XLPE and the dark region is the base material. This means filler is dispersed evenly after treated of ZnO by amino silane and melt compounded with XLPE.



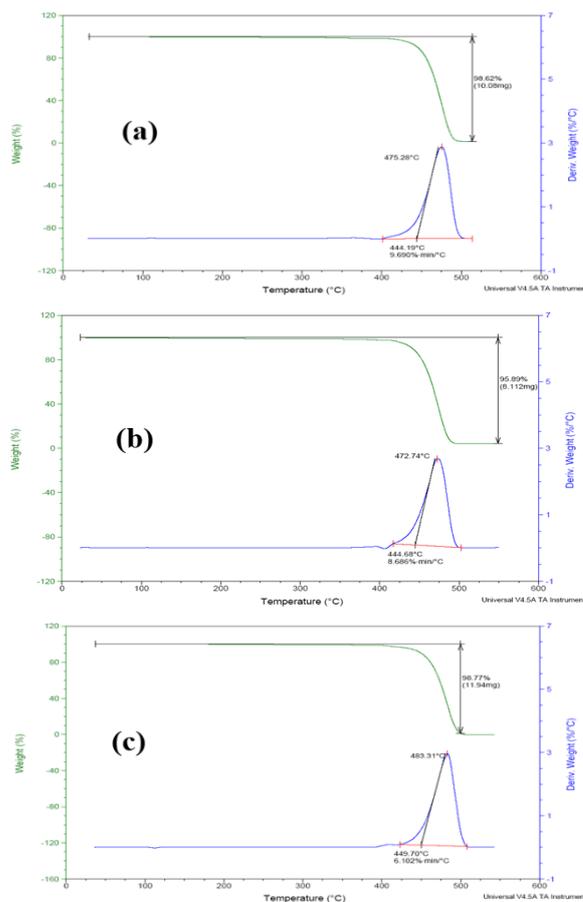
**Fig. 3.** FE-SEM micrographs as cross section area and surface of XLPE/ZnO nanocomposites with non-functionalized (a,c) and functionalized ZnO (b,d)

#### 4.2. Thermo-gravimetric analysis (TGA)

Interpretations of TGA data depend on the initial experimental setup and from the basic percentage weight loss versus temperature (or time); the rate of degradation in polymer samples with the respective independent variable. The onset of time or temperature of the initial weight loss can be considered a loss of volatiles, absorbed water or, lower molecular weight constituents. The onset of irreversible weight loss could suggest the real thermal degradations so that, TGA data as a function of temperature can also be used to follow the thermal recovery of mechanical deformation [35]. In this study, the weight loss at 300 °C, 400 °C, and 475 °C (decomposition temperature) was the main criteria used to determine the thermal stability of nanocomposites. The higher the values of decomposition temperatures indicated the thermal stability of XLPE/ZnO nanocomposites [36]. From Fig.4 and Table1, it is seen that the weight loss values are 0.83, 1.99, and 62.9% at 300, 400, and 475 °C respectively. It means that, its rate of loss decreased with increasing temperature. By the addition of nonfunctionalized and functionalized ZnO nanoparticles the weight loss decreased with functionalized ZnO. Consequently, the decomposition temperature decreased with nonfunctionalized ZnO and increased with functionalized ZnO. This means the addition of functionalized nanoparticles into the XLPE polymer improved the thermal stability. This may be due to the high thermal resistance of the inorganic nanomaterial which has an onset temperature of 580 °C [37-40] or due to the lower mobility of the matrix chains as a result of the strong interaction between the nanoparticles and the XLPE polymer.

**Table.1** Weight loss and decomposition temperatures of XLPE and XLPE/ZnO nanocomposites

Sample	Weight Loss (%)			Decomposition Temperature °C
	300°C	400°C	475°C	
XLPE	0.83	1.99	62.9	475.28
XLPE/ Nonfunctionalized ZnO	1.17	2.44	66.07	472.70
XLPE/ Functionalized ZnO	0.75	1.49	44.89	483.31



**Fig. 4.** TGA of: (a) XLPE (b) XLPE nanocomposite with nonfunctionalized ZnO and (c) XLPE nanocomposite with functionalized ZnO

#### 4.3. Differential scanning calorimetry (DSC) analysis

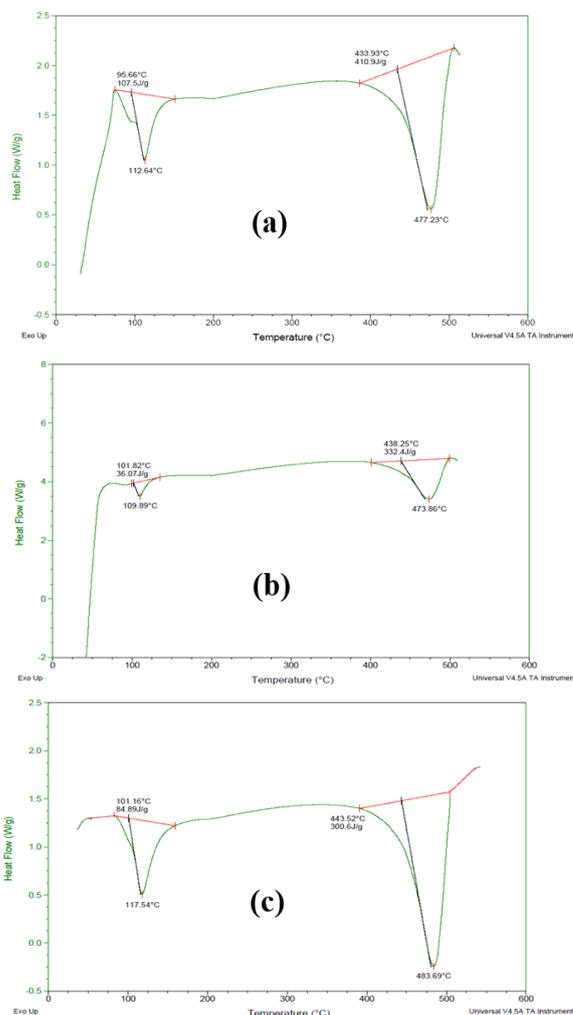
In this section, the effect of incorporating different weights of nonfunctionalized and functionalized ZnO nanoparticles on the thermal behavior of XLPE was studied. When an amorphous polymer is heated, the temperature at which the polymer structure converts to “viscous liquid or rubbery” is called the glass transition temperature ( $T_g$ ). With increasing temperature, polymer transits from the crystalline shape into the viscous flow shape which called melting temperature ( $T_m$ ). This melting process confirms an endothermic peak in the DSC curve [41]. Measurement results achieved from the XLPE and XLPE/ZnO nanocomposite were analyzed by heating at a constant rate of 10 °C/min under a nitrogen atmosphere and the heating interval was 0-600 °C. For

XLPE, it is observed that the glass transition and the melting temperatures were 112.64 and 477.23°C; respectively (Table 2 and Fig 5a).

For XLPE/ZnO nonfunctionalized and functionalized nanocomposites, there are some changes in the heat flow peaks for the two composites. The column diagrams clearly reveal that the peak temperature was decreased by adding nonfunctionalized ZnO as shown in fig 5b. The glass transition temperature was 109.63°C and the melting temperature was 473.75°C (Table 2). However, the reduction in T<sub>g</sub> and T<sub>m</sub> values of nonfunctionalized ZnO nanofiller loading may be due to the many reasons like changes in molecular weight, cross-linking density, and the presence of residues from incomplete reactions. The other possible reasons may be the size of the agglomerated nanoparticles which are certainly larger than the free volume hole sizes in the matrix and therefore the possible slide between the chains will result in increased free volume. On the other side, it can be seen an increase in T<sub>g</sub> and T<sub>m</sub> values in case of using functionalized ZnO, (Fig 5c), nanofiller loading reaches 117.54°C and 483.69°C; respectively (Table 2). The increase in T<sub>g</sub> and T<sub>m</sub> with the incorporating of functionalized nanoparticles due to a few cross-links that developed between the polymer matrix and nanoparticles results in a homogenous distribution of nanoparticles within the polymer matrix and therefore increased the polymer crystallization. It is shown that the T<sub>g</sub> and T<sub>m</sub> in case of functionalized nanocomposite are higher than that of XLPE this indicated that the addition of nanoparticles promoted crystallization at high temperatures.

**Table 2** T<sub>g</sub> and T<sub>m</sub> of XLPE and XLPE/ZnO nanocomposites

Sample	T <sub>g</sub> (°C)	T <sub>m</sub> (°C)
XLPE	112.64	477.23
XLPE/ Nonfunctionalized ZnO	109.63	473.75
XLPE /Functionalized ZnO	117.54	483.69



**Fig. 5.** DSC of (a) XLPE (b) XLPE nanocomposite with nonfunctionalized ZnO and (c) XLPE nanocomposite with functionalized ZnO

#### 4.4. Dielectric Properties of XLPE/ZnO Nanocomposites

The dielectric properties of XLPE/ZnO nanocomposites such as the relative permittivity, dielectric loss ( $\tan \delta$ ), and the dielectric strength were measured. These three parameters measure the quality and insulation properties of the dielectric material used in HV applications.

##### 4.4.1. Relative permittivity and loss factor

Fig.6 shows the variation of the relative permittivity ( $\epsilon_r$ ) and dielectric loss ( $\tan \delta$ ) of XLPE. XLPE/ZnO nonfunctionalized (0.5 wt.%) and functionalized (0.5, 2, 3.5, and 5 wt%) nanocomposites dielectric properties at a wide range of frequencies.

It is obvious that in all samples, the relative permittivity and dielectric losses decrease with increasing the frequency. In most samples, when the frequency increased, the dipoles do not have enough time to get oriented in the direction of the electric field. So that, the materials do not build up high values of polarizability with high frequencies resulting in a decrement of  $\epsilon_r$  values. However, and in contrast, when the frequency decreases, the time scales will increase and most mobile atom groups begin to be generated, resulting in an increase in the observed values of  $\epsilon_r$ . Also, it is seen that all prepared samples have relatively high  $\tan \delta$  values at low frequencies.

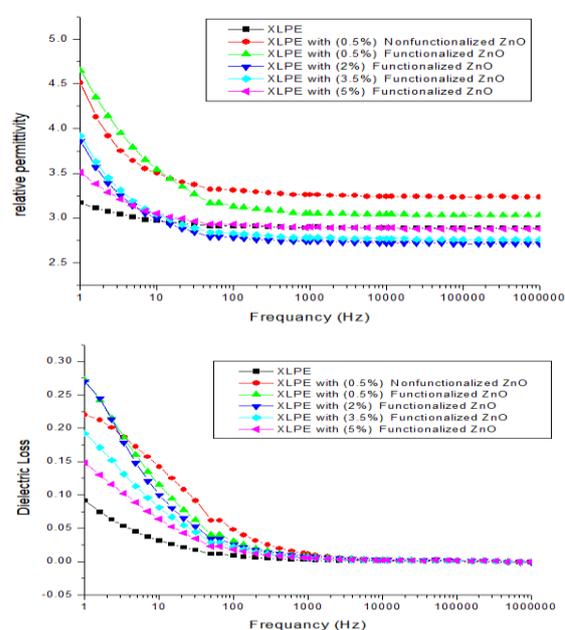
Fig 6a and table 3 show that the values of permittivity of the nanocomposites are varied with the concentration of ZnO. It is observed that, the nonfunctionalized XLPE/ZnO sample have the highest value of relative permittivity which increased by 14.08% than XLPE and has high dielectric losses. This is may be due to the reduction in the interface interaction area between the polymer chains and nanoparticles which results from nanoparticle agglomeration. The agglomerated nanoparticles will act as voids between the polymer chains and facilitate their mobility, and hence working on more molecular polarization. So this sample was choose with a modified ZnO nanoparticles to clarify the effect of this modified nanoparticles on the sample dielectric behaviour.

Fig 6a and table 3, indicate that XLPE/ZnO functionalized sample with 2 wt.% have the lowest relative permittivity value which decreases by about 4.1% at power frequency 50 Hz. This is due to the restriction in the polymer chain mobility because of good incorporation and dispersion of the functionalized ZnO nanoparticles inside these chains. This is an indication of the chemical functionalization of ZnO to enhance their dispersion and compatibility with the polymeric matrix.

Fig 6b shows the curves of the loss factor,  $\tan \delta$ , versus frequencies for different concentrations of ZnO nanocomposites. It is clear that all samples have relatively high  $\tan \delta$  values at low frequencies, and this is may be due to the high leakage current in the test system. At the same time, it can be noticed that  $\tan \delta$  of the nonfunctionalized XLPE/ZnO samples has the highest losses. Also, the amino-functionalized XLPE/ZnO samples have lower values of  $\tan \delta$  than nonfunctionalized one at frequencies up to 1000 Hz. At high frequencies, the losses were not affected by the addition of the nanoparticles. From Table 3, it is seen that at 50 Hz,  $\tan \delta$  for 5 wt.% amino-functionalized XLPE/ZnO have the lowest losses corresponding to other amino-functionalized samples.

**Table 3** Permittivity and loss factor of XLPE and XLPE/ZnO nanocomposites at 50 Hz

Sample	Wt. %	Relative permittivity ( $\epsilon_r$ )	Loss Factor ( $\tan \delta$ )
XLPE	0	2.91	0.0113
XLPE/ Nonfunctionalized ZnO	0.5	3.32	0.0617
	0.5	3.17	0.0403
XLPE/ Functionalized ZnO	2	2.79	0.0339
	3.5	2.84	0.0285
	5	2.93	0.0226



**Fig.6:** XLPE, nonfunctionalized, amino-functionalized XLPE/ZnO nanocomposites (a) relative permittivity, (b) dielectric loss

#### 4.4.2. AC breakdown strength

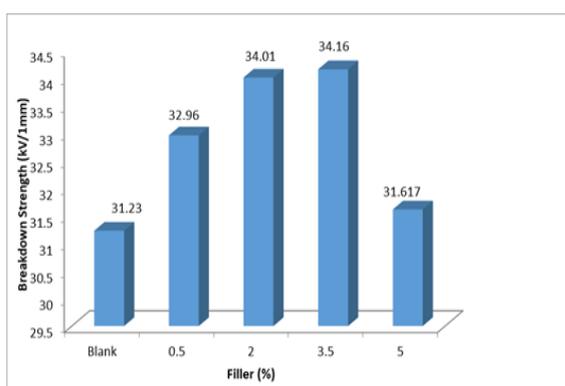
The AC breakdown voltages (AC-BDV) of the nanocomposites are performed with a sphere-to-sphere test cell according to ASTM (D149-09) standard. The test cell was energized by a test transformer (50Hz, 400V/250kV). The AC-BDVs of XLPE/ZnO nanocomposites have been measured. The measured values of AC breakdown strength and the enhancement percentage of functionalized and the nonfunctionalized XLPE/ZnO nanocomposites are shown in table 4. It is seen that the functionalized

XLPE/ZnO nanocomposites are higher than that of the nonfunctionalized one. This may be attributed to the creation of a strong interfacial area between the polymeric matrix and nanoparticles. In addition, by increasing the ratio of nanoparticles, the AC-BDS was increased up to 3.5 wt.% of ZnO nanoparticles, then the AC-BDS began to reduce. The addition of ZnO into the XLPE polymer can increase the AC-BDS, while with a high concentration of nanoparticles a lot of agglomerated particles may be generated and cause a reduction in AC-BDS value. Moreover, the maximum measured value of AC-BDS was happened in the sample with 3.5 wt.% amino-functionalized XLPE/ZnO nanocomposites as shown in Fig.7 which enhanced by 9.39% over XLPE. Otherwise, for nonfunctionalized samples, there is no improvement was observed.

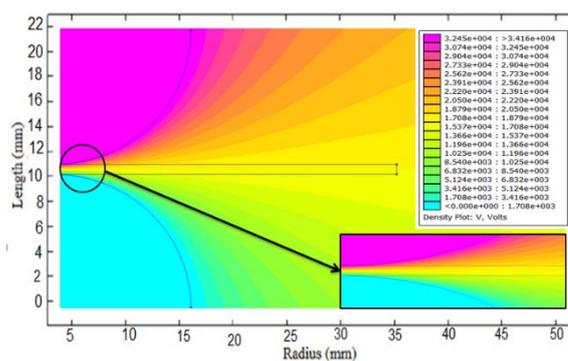
On the other hand, the AC-BDS was obtained using a simulation model on the Femm package, which used the finite element method in a 2-dimensional pattern (i.e. an axisymmetric form). The breakdown voltage applied to the upper sphere was taken from the experimental result, and the lower sphere was grounded. The voltage and electric field distribution inside and around the samples were traced and evaluated. The value of breakdown strength at tipping point of the HV sphere was recorded as shown in Table 4. Fig.10a and fig.10b show the electric potential and electrostatic field distribution in and around the sample with 3.5 wt.% amino-functionalized nanoparticles as a best sample. It is clear that there is a high agreement between the measured and the simulated results.

**Table 4** Measured and simulated rms values of AC-BDS of the XLPE/TiO<sub>2</sub> nanocomposites at sphere-sphere field

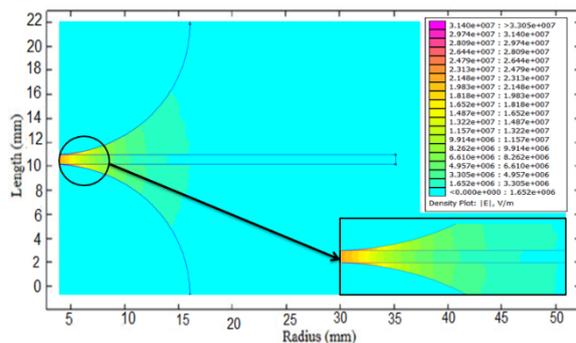
Sample	Wt. (%)	Breakdown strength (kV/mm)	Improvement (%)	Simulated Breakdown strength (kV/mm)
XLPE	0	31.23	0	32.64
XLPE/ Nonfunctionalized ZnO	0.5	25	-19.95 %	27.6
XLPE/ Functionalized ZnO	0.5	32.96	+5.54 %	33.29
	2	34.01	+8.19 %	34.56
	3.5	34.16	+9.38 %	35.55
	5	31.617	+1.24%	31.96



(a)



(b)



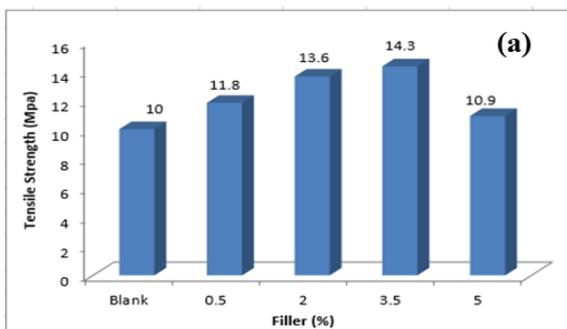
(c)

**Fig.8** (a) AC potential distribution around sphere electrode and along with sample thickness, (b) Electrostatic field distribution inside 3.5 wt.% XLPE/amino-functionalized ZnO nanocomposite for the sphere to sphere configuration

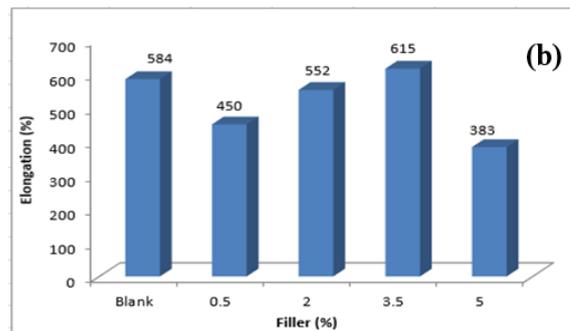
#### 4.5. Mechanical Properties

Fig. 9 shows the relation between the loaded added ZnO and mechanical properties of XLPE sheets. The presence of ZnO incorporated with XLPE slightly enhanced the tensile strength and elongation with optimum strength appeared with 3.5% ZnO.

This indicates that the incorporating of ZnO functionalized nanoparticles enhanced the mechanical properties of XLPE. This behavior in mechanical properties and the increase in the tensile strength value with low loading of nanoparticles have resulted from their high specific surface available for interactions with the polymer chains. Also, the reduction of elongation values with addition of nanofiller is expected for most polymer nanocomposites and that is due to the restriction of the chains mobility that created from the bonding between nanoparticles and polymer matrix [42].



(a)



(b)

**Fig. 9.** Tensile strength (a), and elongation (b) of functionalized XLPE/ZnO nanocomposites with different weight ratios.

#### 5. Conclusion

Cross-linked polyethylene is the main insulation in power cables. Their electrical, physical and chemical characteristics are of a great interest. This paper interested with enhancing these properties, especially its electrical characteristics, using nonfunctionalized and functionalized ZnO nanoparticles which is limited in publishing issues, where most of researchers interested with high and low density polyethylene. In this paper, the industrial scale of XLPE/ZnO nanocomposites with different loadings ratios of zinc oxide nanoparticles was synthesized and developed using the melt blending method. The thermal, mechanical, and dielectric properties represented in; AC BDS,  $\epsilon_r$ , and  $\tan \delta$  of the nanocomposites were measured. It is concluded that, the incorporating of ZnO nanoparticles into the XLPE matrix improved the thermal and mechanical properties of XLPE polymer and the functionalization nanoparticles lead to an excellent dispersion inside the polymer matrix. Larger values of dielectric loss are shown in the low-frequency area, which indicates the interface polarization in XLPE nanocomposites. For functionalized nanocomposites, the breakdown strength was higher than that of the XLPE. As the percentage weight of nanoparticles increased, the interparticle distance decreases, which leads to a hindrance in charge carriers transferring and create a strong bond, which leads to increasing the dielectric strength. However, it is noticed that more addition of ZnO nanoparticles decreased the dielectric strength and that's maybe due to the high concentration of

nanoparticles leads to more agglomeration causing much reduction in AC-BDS.

## 6. Acknowledgement

I would like to express my deep gratitude to El-Sewedy Electric Co., the largest company for manufacturing electric power underground cables in Egypt, for helping us in our research.

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