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Investigating Breakdown Strength Based on Trapping Profile in Cross-Linked Polyethylene (XLPE) Nanocomposites

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Abstract

Mobile charge accumulation can negatively impact the performance of cross-linked polyethylene insulation. This increases the local electric field within the insulation material, reducing the probability of breakdown. The introduction of zinc oxide (ZnO) nanofillers in insulation materials is expected to reduce the mobility of charge carriers. Therefore, the objective of this research work is to investigate the effect of ZnO nanofillers on the breakdown strength of Cross-Linked Polyethylene, based on trapping profiles. The effect of ZnO nanofillers at concentrations of 0.5 wt%, 1.0 wt%, and 1.5 wt% was evaluated by photoluminescence, with the selected range corresponding to low filler loadings that promote uniform dispersion and suppress nanoparticle agglomeration. The result from the photoluminescence test provides two distinct peaks at different energy level, the lower energy level indicates shallow traps that causes premature failure in insulation owning to the ease with which it releases charge carriers back to conduction band promoting formation of conduction pathways, while the higher energy level indicates deep traps that requires greater energy to release the captured charge carriers back to the conduction band which prolong the detention of the charge carriers and in turn retard the formation of conduction pathways. The density of shallow traps decreases with increasing concentration of zinc oxide (ZnO); conversely, the density of the deep traps increases with increasing concentration of zinc oxide (ZnO). As a result, the alternating current (AC) breakdown field strength and reliability of cross-linked polyethylene (XLPE) were improved, as supported by the alternating current (AC) breakdown strength test.

Keywords: *Nanocomposite, trap, energy level, breakdown voltage, breakdown strength.*

1.0 Introduction

Cross-linked polyethylene (XLPE) is a polymeric material that has been extensively applied as an insulator in high-voltage cables owing to its excellent dielectric properties, high flexibility and mechanical strength, good resistance to chemicals, low cost, and easy processing[1]. Despite their relative effectiveness, they are prone to unexpected weather, contamination attacks, and other external stresses, leading to insulation breakdown. Materials that can endure these rigors while maintaining optimal electrical performance are required due to the constantly rising voltages, temperatures, and environmental stresses. However, the incorporation of nanotechnology into XLPE heralds a new era. XLPE nanocomposites are composite materials wherein nanoscale fillers, such as nanoparticles or nanotubes (e.g Zinc Oxide), are dispersed within the XLPE matrix[1, 2]. This deliberate integration of Nano fillers introduces a myriad of benefits that extend beyond the conventional attributes of XLPE. Improvement on trapping efficiency in polymer matrix (epoxy resin, polyethylene) containing Nano filler has been reported by a few researchers[2, 3]. Furthermore, studies on electrical tree growth and the investigation of the effect of Nano fillers in XLPE composite on trapping profile are uncertain and significant to be investigated.

Charge trapping is a fundamental phenomenon in cross-linked polyethylene (XLPE) nanocomposites that has a significant impact on their electrical performance. Trapping is the capture and retention of charge carriers within specific locations, which affects the overall electrical behavior of the nanocomposite. This phenomenon is especially important in high-voltage applications involving XLPE nanocomposites, such as power cables and insulation systems [4-7].

Investigations from the work of previous researchers have shown that the breakdown strength of XLPE matrix increases with an appropriate increase in the concentration of Zinc Oxide nanofillers [8, 9]. However, the knowledge of what happened within the XLPE nanocomposites that makes the breakdown strength improve with the increasing concentration of the Zinc Oxide remains poorly understood.

Several recent studies have explored the use of ZnO nanoparticle-filled polymer nanocomposites to enhance dielectric properties; however, the findings remain varied due to differences in filler concentration, particle size, dispersion quality, and measurement techniques. For instance, a study reported that ZnO nanoparticles could significantly improve the dielectric strength of epoxy composites, attributing the enhancement to the formation of deep trap levels that impede charge carrier mobility [10]. Likewise, another study demonstrated that ZnO nanoparticles are effective in tailoring the trap distribution in polyethylene by introducing interfacial polarization

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and altering the local electric field [11]. However, most of these works were limited to either DC breakdown investigation or focused on high filler loadings (>2 wt%), which often lead to nanoparticle agglomeration and interfacial defects that can deteriorate dielectric performance.

Only a few studies have investigated the influence of low ZnO loadings (≤1.5 wt%) on the trap characteristics and AC breakdown strength of XLPE under identical experimental conditions. For example, a study observed that the dielectric performance of polymer nanocomposites is highly dependent on the filler-matrix interaction at low concentrations [12], but this was not correlated with microscopic trap parameters. Additionally, although photoluminescence (PL) spectroscopy has been employed to analyze trap states in polymers, its correlation with AC breakdown behavior in XLPE/ZnO systems remains inadequately addressed [13, 14]. Furthermore, the reliability assessment of breakdown strength using Weibull statistics in conjunction with microscopic trap analysis has not been comprehensively reported for ZnO/XLPE nanocomposites.

In view of the above, this study aims to fill these gaps by systematically investigating the effect of ZnO nanoparticle concentrations of 0.5, 1.0, and 1.5 wt% on the trap energy levels, trap densities, and AC breakdown strength of XLPE. Photoluminescence spectroscopy is employed to identify the trap states and their distribution, and the results are correlated with macroscopic breakdown performance. The reliability of the breakdown data is further evaluated using Weibull statistical analysis. This integrated approach provides deeper insight into the charge trapping mechanism and offers a scientific basis for optimizing ZnO loading in XLPE insulation materials for high-reliability power cable applications.

2.0 Methodology

2.1 Sample Preparation

Pure XLPE and XLPE doped with 0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO were prepared. The concentration was selected based on reports in previous research [1] and was carefully chosen to investigate the influence of low filler loading on electrical properties while avoiding nanoparticle agglomeration. At low concentrations, nanofillers are more uniformly dispersed within the polymer matrix, which enhances interfacial interactions and promotes effective charge trapping. However, at higher concentrations beyond this range, particle agglomeration may occur, leading to defects that can deteriorate dielectric performance. Therefore, the selected concentrations (0.5–1.5 wt%) represent an optimal range to study the transition in trapping behavior and breakdown strength of XLPE nanocomposites. The prepared samples were placed inside a vacuum oven at 85°C for 24 hours to remove moisture content, after which the samples were mixed and thoroughly blended to ensure a homogenous distribution of the zinc oxide within the polymer matrix by a mechanical mixer (Brabender mixer) at the UTM polymer laboratory, as shown in Figure 1. The XLPE nanocomposites were prepared by fully blending the pure XLPE with ZnO in a Brabender mixer at 135°C for 6 min, and a speed of 60 r/min. The specimens were obtained after cooling at room temperature and were cut into smaller pieces and spread over a plastic sheet for the hot pressing process. The temperature was carefully controlled to ensure the XLPE undergoes cross-linking, a process that enhances its thermal and mechanical properties. Pressure was applied to the mold to compact the XLPE-ZnO mixture and promote proper bonding between the polymer chains and the zinc oxide particles at a pressure of 3 bar for 6 minutes at a temperature of 65°C using a hydraulic hot pressing machine. After the hot pressing cycle, the mold was allowed to cool down gradually. The round specimens with a thickness of 0.16 mm were obtained for the AC breakdown tests and photoluminescence tests.

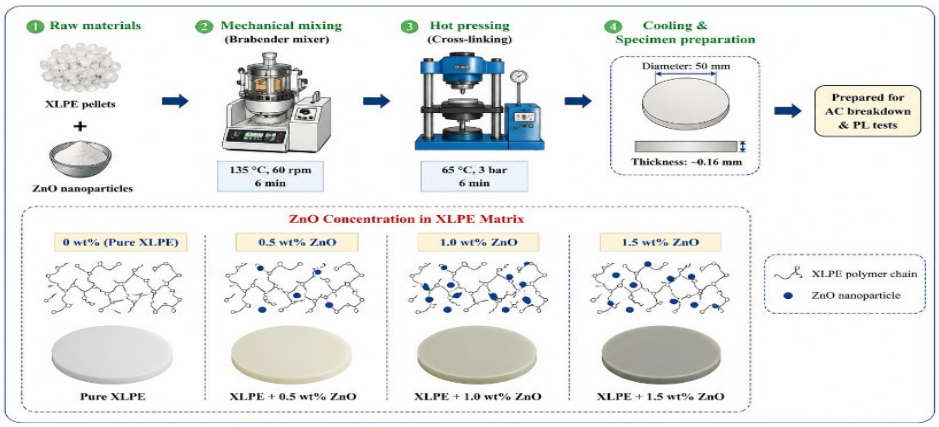

Figure 1: Schematic diagram of the preparation of ZnO/XLPE nanocomposites at different ZnO concentrations: 0 wt% (pure XLPE), 0.5 wt%, 1.0 wt%, and 1.5 wt%

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2.2 AC Voltage Breakdown Test

The experimental setup for the AC breakdown test is shown in Figure 2. It consists of a high-voltage supply connected to a pair of spherical copper electrodes immersed in silicone oil, which serves as an insulating medium to suppress surface flashover and prevent air ionization. The test sample is positioned between the electrodes, and the applied voltage is gradually increased until dielectric breakdown occurs. The corresponding breakdown voltage is recorded for analysis. The AC breakdown experiment was conducted 10 times for each sample to ensure statistical reliability of the results. The obtained breakdown voltage data were subsequently analyzed using the Weibull statistical =23 distribution to evaluate the breakdown characteristics of the XLPE nanocomposites [15, 16]. The Weibull statistical distribution was employed to analyze the breakdown data due to its suitability for describing the probabilistic nature of dielectric failure in insulating materials. It enables reliable estimation of breakdown strength and dispersion characteristics through the scale and shape parameters, providing a robust framework for comparing the reliability and performance of different material compositions.

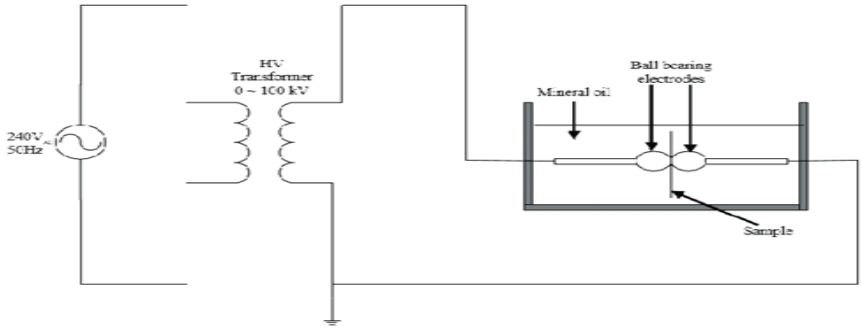

Figure 2: Schematic diagram of the breakdown test [1]

2.3 Photoluminescence Test

Photoluminescence (PL) measurements were carried out to investigate the charge trapping characteristics of pure XLPE and ZnO/XLPE nanocomposites. The experimental setup, as illustrated in Figure 3, consists of a light excitation source, monochromators, a sample holder, and a detection system. A xenon lamp was used as the excitation source due to its broad spectral output. The emitted light from the source was first passed through an excitation monochromator to select the desired excitation wavelength before illuminating the sample surface.

The prepared samples were mounted on a sample holder, and the emitted photoluminescence signal was collected at an angle of 90° relative to the incident excitation beam. This configuration minimizes the detection of scattered light and improves measurement accuracy. The emitted light was then directed through an emission monochromator, which isolates specific wavelengths corresponding to the recombination of charge carriers within the material.

The filtered emission signal was detected using a photodetector, and the output was recorded and processed using a computer-based data acquisition system. All measurements were conducted under controlled conditions with a fixed excitation wavelength of 250 nm, and the emission spectra were recorded over a wavelength range of 270–480 nm. These parameters were selected to effectively capture the relevant optical transitions associated with trap states in XLPE and ZnO nanocomposites.

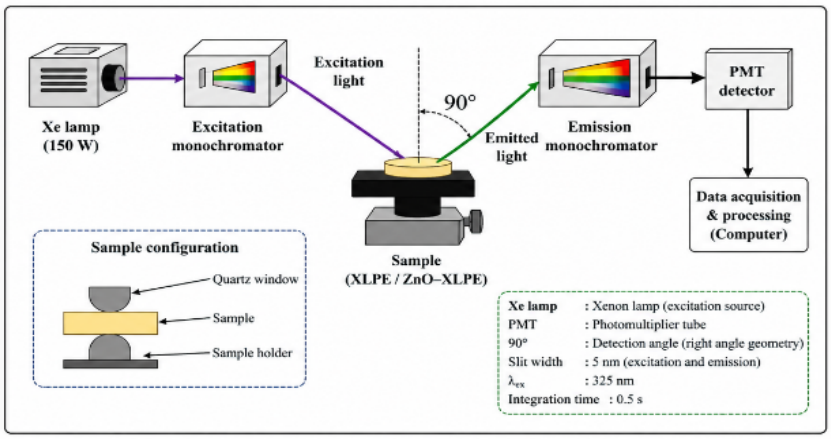

Figure 3: Schematic diagram of the photoluminescence experimental setup.

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3.0 Result and Discussion

3.1 AC Breakdown Characteristics

The Weibull probability distribution was used to model the four samples' ac breakdown field strengths. Figure 4 displays the results of plotting the ac breakdown field strength of pure XLPE and XLPE doped with different concentrations of ZnO nanofillers (0.5 wt%, 1.0 wt%, and 1.5 wt%) against the Weibull cumulative failure probability as the vertical axis. Table 1 also displays the shape parameter (Beta) and scale parameter (Alpha) for each sample. Furthermore, Figure 5 shows a bar chart with the breakdown strengths plotted against the nanofiller concentration, which indicates the trend of how the breakdown strength increases with increasing concentration of the ZnO nanofiller.

Figures 4, 5, and Table 1 show that the addition of 0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO nanofiller to the XLPE matrix slightly increased the breakdown strengths by 7.38%, 13.93%, and 16.39%, respectively

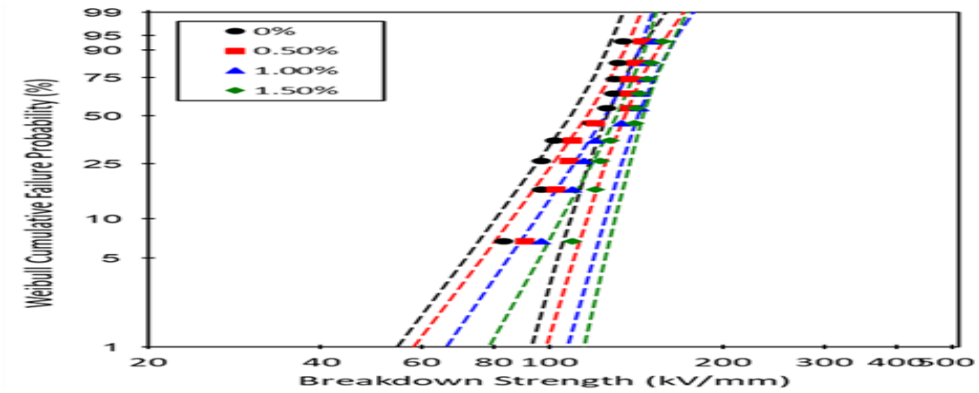

Figure 4: Weibull probability distribution comparing the breakdown field strength of the samples

Table 1: Weibull parameters (scale parameter α and shape parameter β) and corresponding breakdown strength improvement for pure XLPE and ZnO/XLPE nanocomposites

Parameters	Pure XLPE	XLPE+0.5 wt% ZnO	XLPE+1.0wt% ZnO	XLPE+ 1.5 wt% ZnO
Alpha (Kv/mm)	122	131	139	142
Beta	7	8	9	11
Improvement (%)	0	7.38	13.93	16.39

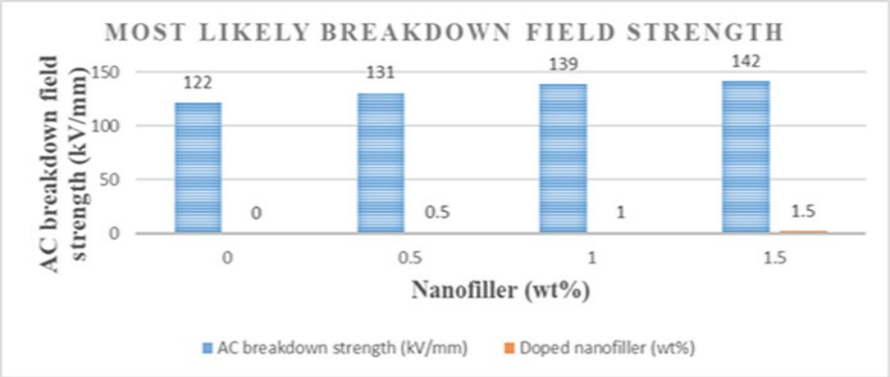

Figure 5: Variation of alternating current (AC) breakdown strength as a function of ZnO nanofiller concentration

The AC breakdown field strengths of pure XLPE and XLPE + ZnO nanocomposites with 0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO are compared in Figure 5. The AC breakdown field strength of the nanocomposites increased with the addition of ZnO. Pure XLPE had an AC breakdown field strength of approximately 122 kV/mm. The AC breakdown field strength in XLPE doped with ZnO nanocomposites increased as the ZnO content rose; at 0.5 wt%, 1.0 wt%, and 1.5 wt% of doped ZnO, the corresponding values were 131 kV/mm, 139 kV/mm, and 142 kV/mm. The pure XLPE in this work had an AC breakdown field strength of 122 kV/mm, which was significantly higher than the AC breakdown field strength of 107 kV/mm of pure XLPE in [32] and the DC breakdown field strength of 220 kV/mm in [33] when compared to other working results. In comparison to the doped samples, the pure XLPE sample has the lowest scale parameter (122 kV/mm) and a relatively low shape parameter (7), which shows a wider distribution of breakdown strengths and a lower overall breakdown strength. By doping XLPE with 0.5%wt ZnO, the shape parameter with value 8 slightly improves, and the breakdown field

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strength rises to 131 kV/mm. This implies a moderate increase in dielectric strength due to the new traps introduced by the ZnO nanofillers. The scale parameter rises to 139 kV/mm at 1.0%wt ZnO doping, while the shape parameter marginally improves. This suggests a slightly more consistent performance and a more notable improvement in breakdown strength, which are probably caused by the improved trapping mechanisms that the ZnO nanofillers provide. With a breakdown strength of 142 kV/mm and a shape parameter of 11, the 1.5%wt ZnO doped sample exhibits the highest breakdown strength and the most consistent performance. The stabilization of the material's dielectric properties is probably achieved more successfully by the traps introduced by the higher concentration of ZnO nanofillers. The most likely breakdown field strength is depicted in Figure 6. 63.2% of the pure XLPE samples failed at 122 kV/mm, 131 kV/mm for XLPE+ 0.5%wt ZnO, 139 kV/mm for XLPE + 1.0%wt ZnO, and 142 kV/mm for XLPE + 1.5%wt ZnO. This suggests that the breakdown field strength increases as ZnO concentration rises from 0 to 1.5%wt. The photoluminescence spectra's depiction of the trapping profiles demonstrates that ZnO doping adds new traps, which are essential to XLPE's dielectric behavior. Charge carriers can be caught by these traps, which will lessen their mobility and stop conduction paths from forming, which would otherwise result in breakdown. The quantity and efficiency of these traps grow along with the concentration of ZnO, resulting in higher field strength [17].

3.2 Photoluminescence Analysis

The photoluminescence intensity of XLPE samples is plotted against wavelength in nanometers (nm) as shown in Figure 6. Every graph represents a distinct sample: pure XLPE and XLPE that has been doped with varying amounts of ZnO nanofiller (0.5%wt, 1.0%wt, and 1.5%wt). The wavelength, which ranges from 270 nm to 480 nm, is represented by the x-axis, and the photoluminescence intensity, measured in arbitrary units (a.u.), is represented by the y-axis. Every sample was stimulated at 250 nm, and emissions were measured between 270 and 480 nm. Plotting the light's intensity against wavelength.

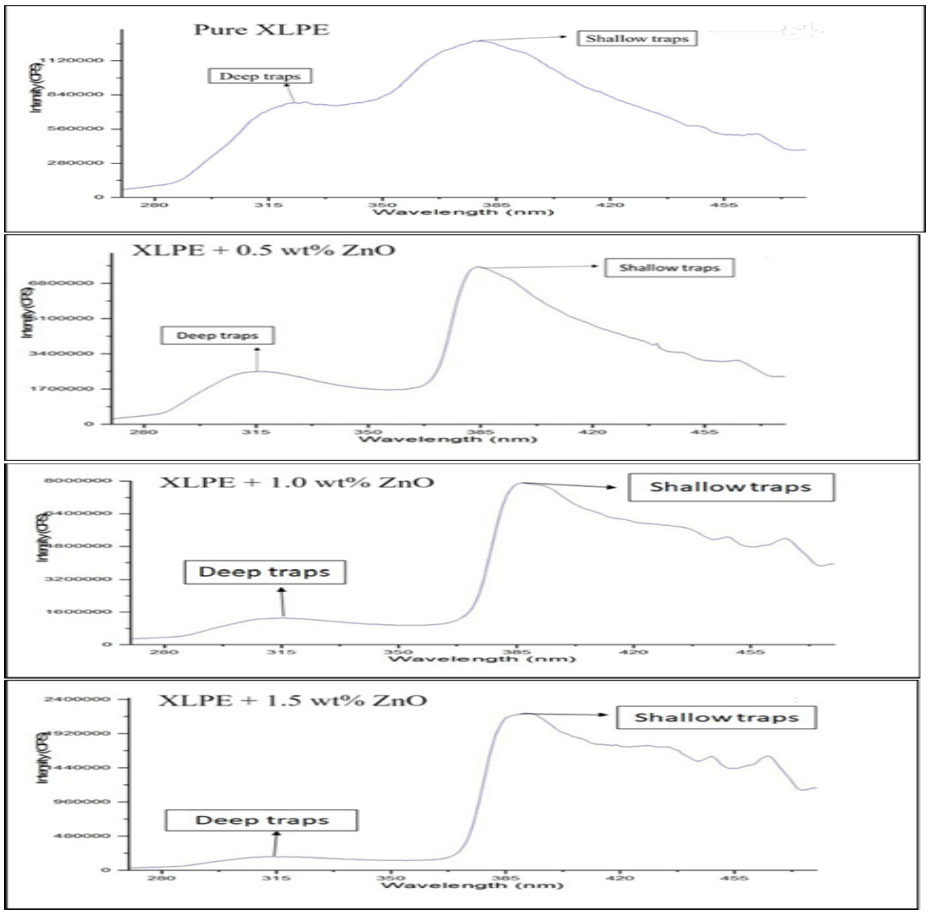

Figure 6: Photoluminescence spectra of pure XLPE and XLPE doped with 0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO nanofillers

Figure 6 shows the result of the photoluminescence test for the XLPE sample, and XLPE doped with 0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO, respectively, in a graphical form with the intensity of the emitted light plotted against the wavelength. Two peaks were present in all graphs, which were named primary and secondary peaks. The corresponding wavelengths at these peaks gave the energy level, which was calculated based on the formula

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$E=hc/\lambda$, where h stands for Planck's constant, c for the speed of light, and λ for wavelength. The energy level helps to identify the particular type of traps, which could either be shallow or deep traps. The lower energy level was associated with shallow traps, and the higher energy level was associated with deep traps. However, the width of the peaks determines the density of these traps, depending on the peak's width (narrowness). A narrow peak indicates a lower density of traps, and a comparatively broad peak indicates a higher density of traps. The intensity of these peaks quantifies the mobility of charge carriers. Higher intensity indicates a large number of mobile charge carriers, while lower intensity indicates a lower number of mobile charge carriers.

The pure XLPE graph depicts the photoluminescence (PL) spectrum, which reveals a broad emission primary peak and secondary peak with corresponding wavelengths of around 385 nm and 320 nm, respectively. The energy levels corresponding to these peaks are approximately 3.22 eV and 3.88 eV, respectively, based on the formula $E=hc/\lambda$. The energy level at the primary peak indicates shallow traps, and multiple shallow traps are distributed, as indicated by the broad peak, causing quick cycles of trapping and detrapping, which promote the formation of conduction pathways that lead to premature failure.

However, the XLPE doped with 0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO also depicts the photoluminescence spectra as shown in Figure 7. Although the graphs follow a similar pattern of behavior when compared with that of pure XLPE, with the primary peak energy level of 3.22 eV and a slight increase in the secondary peak energy level to 3.94 eV, there exist distinct differences in the intensities of the primary and secondary peaks, as well as in the width of the peaks. The primary and the secondary peaks of the pure XLPE are at intensities 1,134,000 lux and 77,000 lux, respectively, while the primary and the secondary peaks of the doped samples (0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO) are at 7,650,000 lux and 2,550,000 lux, 7,950,000 lux and 1,450,000 lux, 2,200,000 lux and 160,000 lux, respectively. Likewise, the width of both the primary and the secondary peaks decreases with increasing nanofiller (ZnO) concentrations. The noticeable change in the width of the XLPE samples at the primary peak shows that the introduction of the nanofiller modifies the trapping profile by decreasing the density of the shallow traps. The density of the shallow traps decreases with increasing concentration of the nanofiller, which is indicated by the decrease in the width of the primary peak. The pronounced appearance of the secondary peak in the doped samples, as well as the changes in the intensities and width of this peak, show that the addition of ZnO introduces deep traps. The density of the deep traps increases with increasing concentration of the nanofillers because the width of the secondary peaks increases with increasing concentration of the nanofillers.

The effect of shallow traps can be seen in their low energy level. Shallow traps require less energy to capture and immobilize charge carriers from a conduction band, and with a small increase in temperature or applied electric field, it releases the captured charge carrier back to the conduction band. So at a higher density of shallow traps, quick cycles of trapping and detrapping are promoted, and this causes a frequent formation of conduction paths that subsequently lead to premature failure. However, the addition of ZnO nanofiller at an appropriate amount modifies the existing shallow traps by decreasing their density and introducing new traps (deep traps), which are comparatively at a higher energy level compared to the shallow traps. The deep traps require higher energy to capture charge carriers and as well needs greater increase in temperature or applied electric field to release the captured charge carriers back to the conduction band. This reason makes deep traps to prolong the detention of the captured carriers and, by so doing retard the formation of conduction paths and, in return, improve the strength of the materials.

4.0 Conclusion

In conclusion, the Weibull probability distribution evaluates the material's strength and dependability under AC breakdown testing, while the photoluminescence spectra reveal information about the energy levels, trap types, and densities in the material. The breakdown strength of pure XLPE was 122kV/mm, and that of XLPE doped with 0.5 wt%, 1.0 wt%, and 1.5 wt% ZnO was 131kV/mm, 139kV/mm, and 142kV/mm, respectively. The result showed that the breakdown strength of the XLPE sample increases with increasing concentration of ZnO nanofiller. The result from the photoluminescence test showed two distinct peaks, primary and secondary peaks, at different energy levels of 3.22eV and 3.94 eV, respectively. The lower energy level indicates shallow traps, and the higher energy level indicates deep traps. The introduction of the nanofillers modified the existing trapping profile by decreasing the density of the shallow traps and reintroducing deep traps, as well as increasing their density with increasing nanofiller concentrations. The introduced traps (deep traps) prolong the detention of the captured charge carriers and retard the formation of the conduction pathways, thereby improving the breakdown strength. The densities of the deep traps increase with increasing concentration of the nanofiller, and this is the reason behind the increase in the breakdown strength with increasing concentration of the nanofiller, and thus the correlation.

The photoluminescence test provided the results of the test in a graphical form for the trapping profile to be analyzed. However, it only entails how the density of the shallow traps decreases, and the density of the deep traps increases with increasing concentration of ZnO nanofiller. In the future, advanced technological equipment can

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be used to visualize the types of traps so that their densities can be quantified in order to know the percentage increment provided by a particular added concentration of ZnO.

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