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Malaysian Polymer Journal, Vol. 6, No. 1, p 58-69, 2011
Available online at www.fkkksa.utm.my/mpj

PRIMalaysian Polymer Journal

Polymer Nanocomposites in High Voltage Electrical Insulation Perspective: A Review

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ABSTRACT: Polymer nanocomposites have attracted wide interests in various industries. This new class of material is capable of providing significant improvements in combined electrical, thermal and mechanical properties. Although the potential use of polymer nanocomposites in electrical insulating industry has only recently begun to be explored, a great number of researches have been conducted with regards to high voltage electrical insulation performance. However, it is found that the fundamental physics and chemistry concerning the property enhancement due to the incorporation of nanocomposites is still poorly understood, and there is still room for improvement in this research area. This paper serves to highlight some of the past developments of polymer nanocomposites and to inspire some potential fields that can be explored in high voltage electrical insulation perspective. Effect of the electrical discharges that causes the surface tracking and partial discharge phenomena on the polymer nanocomposites are the main subjects to be discussed in this paper.

Keywords: Nanocomposites, nanodielectrics, tracking resistance, partial discharge

1.0 INTRODUCTION

Polymer nanocomposites are defined as composites in which small amounts of nanometer sized fillers are homogenously dispersed in polymers by several weight percentages (wt%). As defined, the fillers added to the matrix are very small in quantity, normally less than 10 wt%. Unlike conventional composites, or known as the polymer microcomposites, the amount of microfillers is so much that it can reach up to 50 wt% of the total materials weight [1].

In order to grasp a better understanding on polymer nanocomposites, Tanaka et al. [1] have sought to further compare it with polymer microcomposites in another two major aspects, namely the size of the fillers and the specific surface area of the composites. Nanocomposites are in the range of nanometers in size (less than 100 nm), different with three orders of magnitude in length as compared to microcomposites. This would mean a difference of approximately nine orders in their number density. Therefore, the distance between neighbouring fillers are much smaller in nanocomposites than in microcomposites. In terms of specific surface area, nanocomposites have high specific surface area of fillers (about three orders larger than microcomposites). With this, the interaction of polymers matrices with fillers is expected to be much more in nanocomposites.

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While the conventional microcomposites can alter certain desired properties of the composite materials (e.g. mechanical and thermal properties), it often comes with the compromise of other properties being negatively affected (e.g. electrical properties). Interestingly, the newly emerging polymer nanocomposites provide significant improvements in combined electrical, thermal and mechanical properties [2]. These profound impacts create great benefits specifically to the high voltage insulating industry, especially in electrical properties enhancement.

Although polymer nanocomposites have drawn research interest in high voltage electrical insulating society, the fundamental physics and chemistry leading to the property enhancement is poorly understood and much remains unexplored. This paper highlights some of the past developments of polymer nanocomposites and inspires some potential fields that can be explored in high voltage electrical insulation perspective. Effect of the electrical discharges leading to surface tracking and partial discharge phenomena on polymer nanocomposites are the main subjects to be discussed in this paper.

2.0 RESEARCH BACKGROUND

Polymer nanocomposites have been an active research area for decades due to its promising properties enhancements. According to Farzana Hussain et al. [3], the first commercialization of polymer nanocomposites appeared in 1990 when Toyota Motor Corporation introduced nylon-6/clay nanocomposites to fabricate timing belt covers for their cars [4]. Since then, various automotive industries followed the use of polymer nanocomposites in their manufacturing. The examples are the applications of nylon-6/clay nanocomposites for engine covers on Mitsubishi's Gasoline Direct Injection engines and the utilization of polyolefin/clay nanocomposites as a step assistant component for General Motor Company Safari and Chevrolet Astro vans [4-7]. This is then followed by the widespread use across other industries such as electronics, optics and food packaging industries.

Development of polymer nanocomposites in high voltage insulating industry has been quite slow as compared to others. The idea of using polymer nanodielectrics in electrical insulation was inspired by Lewis [8] in 1994 when he published a paper entitled "Nanometric Dielectrics". In the paper, Lewis anticipated the property changes that would benefit electrical insulating applications due to nano-inclusion. However, the push to develop nanodielectrics was not focused much on that time. It was until early 21^{st} century that researchers began to look into it when some promising results on property changes have been successfully documented.

Generally, polymer nanocomposites consist of three main constituents, namely the polymer matrix, the nanofiller and the interaction zone – the interface between the matrix and the filler, which is said to play the major role in the property enhancement of polymer nanocomposites [1, 9]. A simplified diagram illustrating the constituents of polymer nanocomposites is as shown in Figure 1. The polymer matrix can be further divided into three main categories: thermoplastics, thermosettings and elastomers. On the other hand, the nanofillers can be classified according to their dimensions: one-dimensional (or normally referred as thin platelets), two-dimensional (or normally referred as nanowires and nanotubes) and three-dimensional (or normally referred as inorganic oxides). For insulation purpose, the nanofillers of interest can either be one-dimensional: clays or layered silicates, or three-dimensional: silica (SiO_2), alumina (Al_2O_3) and titania (TiO_2).

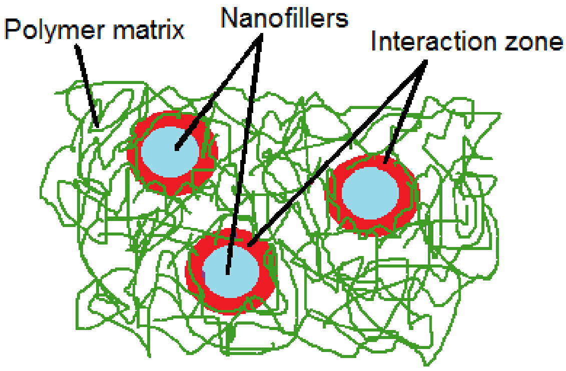

Figure 1: Simplified diagram illustrating constituents of polymer nanocomposites.

Due to the distinct properties of nanocomposites, researchers around the world have looked into several possibilities of nano-sized particles to be combined with base polymers. Examples of nanocomposites currently under development are polyolephins/clays nanocomposites, epoxies/inorganic oxides nanocomposites, elastomer/carbon nanotubes nanocomposites, ethylene-vinyl copolymers/graphite nanocomposites and polyethylene terephthalate /ceramics nanocomposites [10], as summarized in Table 1. Various electrical properties of polymer nanocomposites have also been investigated for high voltage insulation application. Among them are dielectric breakdown strength, permittivity, dissipation factor, space charge formation, partial discharge resistance and tracking resistance. Experimental works on these properties have shown promising results in insulation perspectives.

Table 1: Nanocomposites currently under development.

Base Resin	Nanofiller
Polyolephins	Clays
Epoxies	Inorganic oxides
Elastomer	Carbon nanotubes
Ethylene-vinyl copolymers	Graphite
Polyethylene terephthalate	Ceramics

3.0 ELECTRICAL INSULATION – PAST DEVELOPMENTS AND POTENTIAL FIELDS OF EXPLORATION

The earliest experimental work on polymer nanocomposites in electrical insulation perspective was credited to Henk et al. [11] and Nelson et al. [12] when they documented some potential benefits of polymer nanocomposites. In their research works, the authors highlighted the unusual properties of polymer nanocomposites, which were very different as compared the base polymer and the so called polymer microcomposites (polymer composites added with microfillers).

One of the most important property changes of nanocomposites is the enhancement in dielectric breakdown strength which is found when the filler particles attain nanometric dimensions. This property has in fact been widely documented in many literatures [10, 13-23]. Not only this, other electrical properties, such as permittivity, dissipation factor, space charge formation, partial discharge and tracking resistance were also found to be favorable when polymer nanocomposites were introduced.

Although there is evidence on enhanced dielectric properties of polymer nanocomposites, fundamental physics and chemistry concerning their property changes are not well understood. It is speculated that the interfacial area (interaction zone) is the main factor that contributes to the drastically enhanced insulating properties of nanocomposites [13, 14, 24, 25]. As shown in Figure 2, Nelson [10] correlated the radius of particle to the surface area and suggested that when the size of the fillers is reduced, the specific surface area becomes very large. The interfacial region between nanoparticles and the matrix has a high volume fraction because of the high surface-to-volume ratio of the fillers [15]. As a result, the properties of the nanomaterials become altered.

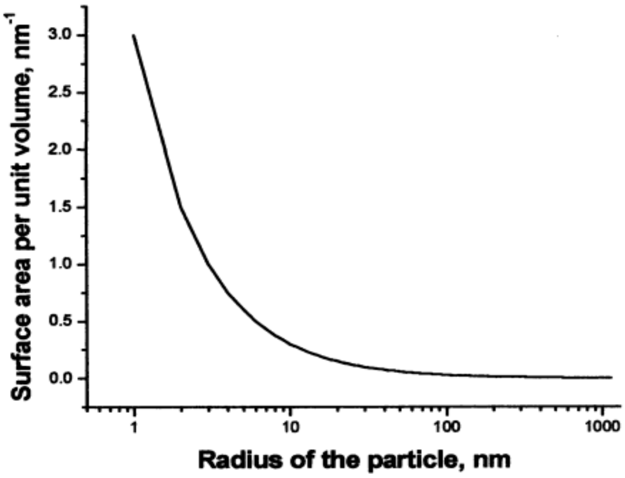

Figure 2: Surface-to-volume ratios of nanocomposites as a function of nanoparticle size [10].

There are also claims that charge transport is of utmost importance in improving the dielectric strength and electrical erosion of nanocomposites [26, 27]. Montanari et. al. [28] investigated nanosilicate filled polypropylene and ethylene-vinylacetate nanocomposites and they found a new relaxation process which they thought to be related to the charge trapping at the interfaces between the nanofillers and the polymer. The magnitude of the internal charge is much less for nanocomposites and the dynamics of charge decay are much faster for nanocomposites [14]. Nelson et al. [29] showed that lower and redistributed space charge is due to the presence of homopolar charge adjacent to cathode, which is contrary to heteropolar charge near cathode for microcomposites. However, Tanaka [30] in his attempt to assign the polarity of charge formed in the composites to his proposed multi-core model, failed to draw conclusion on whether charge formed near the electrodes is homo or hetero, because space charge distribution is complicated, and affected by unknown conditions. Therefore, available data is very limited and questions remain on the electrical property changes of nanocomposites.

3.1 Tracking Resistance

In high voltage engineering, tracking is a process of formation of permanent conducting path across the surface of insulation due to surface erosion under voltage application. This happens to all kinds of polymeric insulators used for outdoor applications. These outdoor polymeric insulators get coated with dust or moisture during service, causing the formation of conducting film on the surface. Since voltage is applied, the film will start conducting, resulting in the generation of heat, and thus causing the surface to become dry. The conducting film becomes separated due to drying, and sparks happen which damage the surface of the insulator. Since polymers are organic insulating materials, the dielectric carbonizes at the region of sparking, and the carbonized regions act as permanent conducting channels resulting in increased stress over the rest of the region. This process is cumulative, which finally resulted in the insulation failure when the carbonized track bridges the entire distance.

Over the past few decades, researchers around the world have been looking for ways to increase the tracking resistance of polymeric insulators in order to increase the service life of the equipment. One of the very famous approaches is to add inorganic fillers to polymers to form the so called polymer microcomposites. For example, Piah et al. [31] investigated the effect of alumina trihydrate fillers on the surface tracking and erosion resistance of natural rubber and linear low density polyethylene blends. Experimental results shows improved surface tracking and erosion resistance of the compounds. Although the use of microcomposites can achieve favorable tracking enhancement, it is said that tracking resistance of polymeric insulators should be further improved to attain greater reliability. An illustration of the tracking test modified from [32] is given in Figure 3.

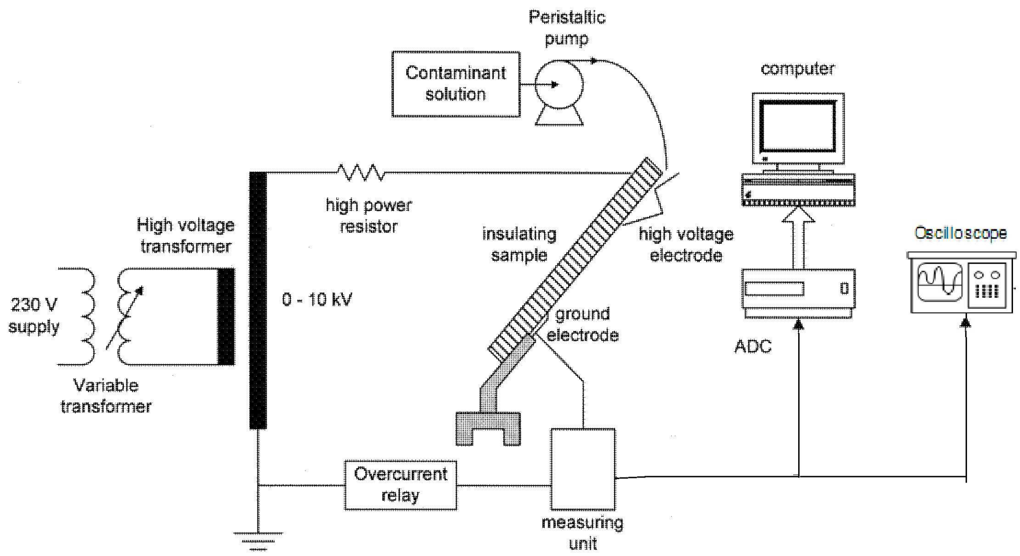

Figure 3: Experimental setup for tracking test based on BS EN 60587: 2007, modified from [32].

Thanks to the recent advancement in the field of nanotechnology, nanocomposites have drawn closer attention in improving the tracking resistance of polymeric insulating materials. As the research on polymer nanocomposites in high voltage insulation is still at its infancy stage, much remains to be explored and explained. Although many investigations have shown promised results on the properties enhancement of polymer nanocomposites, but available data on the tracking resistance is very limited. Tanaka [30] highlighted such an issue when the multi-core model was proposed for polymer nanocomposites in 2005. In the paper, Tanaka highlighted that there is no sufficient data yet for tracking performance to correlate with the multi-core model. It is assumed that the tracking resistance might perform in the same way as partial discharge characteristics.

In 2006, tracking performance data on polymer nanocomposites was published by El-Hag et al. [33]. The authors studied the tracking and erosion resistance of nanosilica-filled silicone rubber and confirmed that the composites depict significant resistance to erosion as compared with micro-filled silicone rubber composites. Using the ASTM 2303 inclined-plane test, they found that a 5 wt% of nanofiller resulted in less eroded mass than did 30 wt% of microfiller incorporated in silicone rubber. Further investigation showed that 10 wt% of nano-filled silicone rubber gives an even better resistance for the nanocomposites. However, it is still not understandable why the increase in content up to

10 wt% can still give favorable results in tracking resistance. This is because it is generally speculated that 5 wt% is the optimum value to improve the properties of nanocomposites. If the content is increased further, it might cause the adverse effect to the properties.

Sarathi et al. [34], on the other hand, observed that the tracking time of aged epoxy nanocomposites is high as compared to the tracking time of pure epoxy material. The test was conducted under IEC 60587 Standards. However, it should be noted that this favorable results applies to only certain test specimens. Careful observation shows that adding nanoclay to epoxy reduces some of the specimens' tracking time as compared to the pure epoxy. This is due to different ageing conditions applied to the samples. The reason behind this is unclear, and this certainly requires further experimental works.

Until now, there is not much available literature to further confirm the tracking performance of polymer nanocomposites. Experimental results obtained thus far are scanty. From this point of view, it can be seen that investigation into the tracking resistance of polymer nanocomposites would be of great importance, especially in confirming its performance with nanofillers.

3.2 Partial Discharge Performance

Partial discharge happens in all types of polymeric insulators. It is defined as localized electrical discharge that only partially bridges the insulation between conductors and which may or may not occur adjacent to a conductor. Partial discharges are in general a consequence of local electrical stress concentrations in the insulation or on the surface of the insulation.

There are mainly four types of partial discharges. They are internal discharge, surface discharges, corona and treeing. Internal discharges occurs in inclusion of low dielectric strength, usually gas filled cavities. This type of discharge is very crucial and has large impact on polymeric insulation. Meanwhile, surface discharge, occurs if there is a stress component parallel to dielectric surface. The discharges extend beyond the region where the original surface component of the electric field is high enough to cause discharges. However, this type of discharge is less concentrated and less dangerous than internal discharge. Corona discharge, on the other hand, happens in air insulation, and is normally not dangerous. Another discharge, called treeing, is actually caused by series of internal discharge.

Since the introduction of polymer nanocomposites, there have been various experimental works conducted on partial discharge characteristics of those insulating materials. To name a few, Tanaka et al. [1] investigated the partial discharge resistance of epoxy/layered silicate nanocomposites. In the experiment, the authors concluded that partial discharge resistance of polymer nanocomposites can be significantly improved by adding just a small amount of nanofillers into epoxy resins. Another experimental work by Kozako et al. [35] also confirmed that only 2 wt% of nanofiller is sufficient to improve the partial discharge resistance of polyamide/layered silicate nanocomposites.

Recently in 2008, Tanaka et al. [36] once again highlighted that epoxy/clay nanocomposites were superior in partial discharge resistance compared to base epoxy resins. The conclusion was drawn based on the evaluation on the depth of erosion. At the same time, Maity et al. [37] researched on the surface discharge degradation of metal oxide nano-filled epoxy. It was documented that nano-alumina and nano-titania filled epoxy yielded considerably improved resistance to surface discharges. It is speculated that metal oxide particles act as reinforcement to the bulk matrix and thus prevent erosion of the bulk matrix.

There are undeniably many experimental results published on the enhancement of partial discharge property of polymer nanocomposites. Unfortunately, most of the experimental works on partial discharge activities concentrated on surface discharges according to IEC (b) rod-plane electrodes configuration. Recall from the types of partial discharges previously defined, internal discharges are more crucial and dangerous as compared to surface discharges. Therefore, literature on internal discharges of polymer nanocomposites should have some points of discussion, since it brings larger impact on insulating materials.

Such literature on internal discharges was once published in 2001 by Henk et al. [38], who investigated the effect of nanoparticle amorphous silica dispersion in epoxy and polyethylene respectively. It was observed that nano-silica had strong effect of increasing partial discharge endurance of thermosets (epoxy & cross-link polyethylene). However, for thermoplastics (low density polyethylene and medium density polyethylene), no effect was observed.

Later in 2007, Lorenzo et al. [39] conducted internal discharge test upon layered nanosilicates filled epoxy resins. The increment of lifetime was found on those materials. Besides that, higher shape factor of Weibull distributions was also found, whereby the material becomes more homogeneous (smaller content of weaker points, generally consisting of macrovoids).

Available results on internal discharges tests for polymer nanocomposites are very limited that there can hardly be any other literatures found. Whether polymer nanocomposites can really enhance the internal discharge characteristics of polymer nanocomposites, much remains to be explored. Therefore, more available data on internal discharges of polymer nanocomposites have to be collected to further confirm the results thus far obtained. Figure 4 shows a test cell configuration that can be used for internal discharge test.

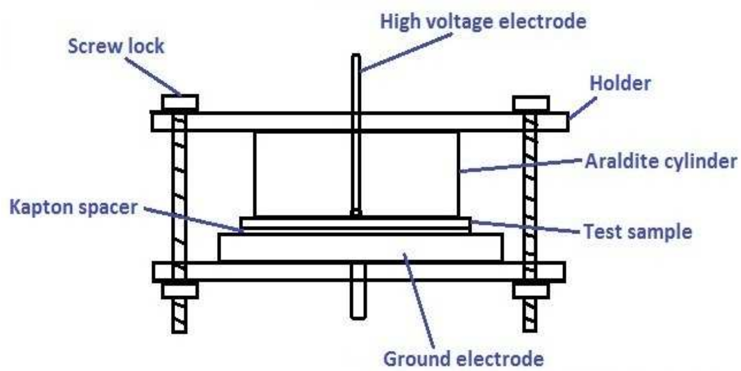

Figure 4: Test cell for internal discharge test according to CIGRE Method II.

3.3 Polyethylene Nanocomposites

From literature review [33, 34, 40-47], currently available results on tracking resistance of polymer nanocomposites concentrated on the use of thermosetting as the host matrix. The use of nanofilled thermoplastics can hardly be found, especially in terms of tracking performance. Therefore, the performance of thermoplastics added with nanoparticles, in regards with tracking resistance, remains a mystery. For this reason, polyethylene thermoplastics would be of great interest to be explored, since polyethylene have already had wide applications in high voltage engineering.

In 2004, a study [48] was undertaken to investigate the tracking phenomena in different polymeric insulating material. It is undeniable that up to now, silicone rubber is still the best outdoor insulator. However, the study shows that high density polyethylene has good performance under alternating current (AC) test environment, and the authors recommended the addition of fillers which could further improve its tracking property. Another experimental analysis on tracking characteristics of pure high density polyethylene was conducted by Sarathi et al. [49] in 2004, and it is found that high density polyethylene would be ideal for low voltage application. It should be reinstated that the test done is based on pure polyethylene. As suggested earlier, filled polyethylene would be advantageous over unfilled polyethylene. Therefore, investigation into tracking performance of high density polyethylene nanocomposites would give an insight into the potential use of high density polyethylene nanocomposites as outdoor insulators in high voltage applications.

As mentioned earlier, partial discharge, which is a very important characteristic leading to the breakdown of high voltage insulators, happens in all kinds of polymeric insulators. There have been various experimental works on partial discharge resistance of polyethylene. However, most of the works focused on the use of low density, linear low density and cross-linked polyethylene. In addition to the insufficiency works on partial discharge previously mentioned, there was also very little attention drawn into partial discharge characteristics of high density polyethylene.

Recently in 2009, the use of high density polyethylene nanocomposites in electrical insulation perspectives has just been published by Shah et al. [50]. The authors investigated various electrical properties of the nanocomposites, particularly dielectric strength, volume resistivity and surface resistivity. The dielectric strength was found to be increased significantly with the increase in nano-clay content up to 5 wt%. Both the volume and surface resistivity were also found to be increased. This has yet shown the potential use of high density polyethylene nanocomposites in high voltage industries. Since the research on high density polyethylene nanocomposites is still very new, exploration into its tracking and partial discharge characteristics would certainly provide invaluable knowledge towards its electrical insulating performance as a whole.

4.0 SUMMARY

Although polymer nanocomposites have attracted a wide interest in electrical insulating society, the fundamental physics and chemistry behind the property changes is not well understood. Additionally, most of the researches focused on the breakdown strength, loss, permittivity, space charge, and partial discharge characteristics. Available data on tracking characteristics of polymer nanocomposites are very limited, and the experimental results obtained thus far are scanty. On the other hand, most of the partial discharge activities concentrated on the surface discharge test methods. Internal discharge characteristics of polymer nanocomposites are not well investigated. Whether the use of polymer nanocomposites can really enhance the tracking and internal discharge characteristics, much remains to be explored.

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