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"**Electricity Supply to Africa and Developing Economies …. Challenges and opportunities.**"

Technology solutions and innovations for developing economies

Developing reproducible electrical tree-resistance epoxy nanodielectric with improved thermal performance.

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Abstract: Insulation is commonly regarded as the weakest part of most electrical equipment. In developing sustainably reliable electric power systems (such as in the context of developing economies), the reliability of electrical insulation therefore becomes one of the focal points of engineering efforts. Two of the main contributors to high voltage insulation failures are thermal and electrical stresses. The failures may be mitigated using nanocomposite material as electrical insulation. Recent state-of-the art review by Cigré has shown that nanodielectric technology is still in its infancy and has yet to move from the laboratory to the domain of full scale manufacturing. In the review however, studies on electrical tree resistance as a performance indicator on nanodielectrics was neglected. The ability to endure electrical treeing degradation is a good measure of the quality of solid electrical insulation. The purpose of the present work is to firstly demonstrate innovations to the effect that nanodielectrics can be a viable technology customised for applications in the context of Sub-Saharan Africa for sustainable power systems development. The improved electrical treeing endurance and thermal performance of the developed nanodielectric epoxy material through use of carbon nanospheres and hexagonal Boron Nitride in an epoxy matrix is presented.

1 Introduction and Background

Power utilities in developing economies such as Eskom in South Africa are pressured to provide reliable electricity supplies at relatively lower costs, and for free in some cases. In order to achieve the contradicting demands, it becomes inevitable to be smart with technology. One of the major contributors to increased operational cost is insulation failure [1]–[3].

In 2003 the Council on Large Electric Systems (Cigré) published a study on the causes of failure in 76 hydro generators [1]. The study showed that two of the main contributors to high voltage insulation failure were thermal and electrical stresses. While insulation is engineered to last for decades, the statistics highlight that premature failure of insulation plays a major role in the faults on generators, motors, transformers, cables and other electrical equipment [4], [5].

In developing economies, the reliability challenges of equipment are exacerbated often by non-ideal operational conditions resulting in equipment being subjected to overstress such as overloads. Currently research in nanodielectric technology is delivering results with the potential to revolutionise the existing insulation technology for improved reliability. The immediate beneficiaries would be the developing economies power systems that are often subjected to extreme operational conditions.

Nanodielectric technology entails improving the conventional insulation quality through the addition of nanoparticles during the manufacturing process. Lewis [6] suggested in 1994 that for insulation to be significantly improved, the size of particle additives needed to decrease to the nanoscale and then added to insulation material. Micro, submicro and nano fillers in host insulation in certain situations allow for electrical, chemical, thermal and mechanical properties of the insulation to be strengthened [7]. Microparticles have already been widely used in silicon rubber-based insulation, but in certain polymers, microparticles perform as defects and therefore have not found many new applications [8]–[10].

The benefits of adding nanofillers are firstly attributed to the high surface area to volume ratio and secondly to establishment of interaction zones (also termed interphase) around the individual nanoparticles [11], [12]. In the late 20th century, ASEA Brown Boveri (ABB) was the first to demonstrate that the thermal conductivity of machine winding insulation could be doubled by the use of aluminium oxide powder [13]. In light of these developments, as the particle size decreased, the overall improvement to the insulation increased because of the interphase changing the properties of the insulation around the particles [14], [15].

Submicro and nanoparticles have given significant improvement effects due to the large ratio of the interphase to particle size; provided there is a good distribution and dispersion of the submicro/nanoparticles when compared to microparticles [16]–[19]. Dispersion refers to the extent to which individual particles are separated from each other, and distribution refers to the spreading of particles/groups of particles inside the insulation [19], [20].

In Brazil a pilot research and development project is underway where nanodielectric material is used as insulation in generator windings [21]. In August 2016 Cigré published a technical brochure presenting the current state-of-the-art knowledge on functional nanomaterials for electric power applications [22]. In the brochure, it was highlighted that firstly, nanodielectric technology that has developed over the last 10 years is still in its infancy as it is still to move from the laboratory to the domain of full scale manufacturing. Secondly the brochure did not cover studies on electrical tree resistance as a performance indicator of nanodielectrics.

Electrical treeing is an insulation degradation mechanism that manifests as tree shaped air-filled micro tunnels growing into the insulation in the areas of enhanced electric stress. The ability to endure electrical tree degradation can therefore be regarded as a 'litmus test' of solid insulation quality. A reasonable body of knowledge on nanodielectrics electrical treeing research has been established in the literature [23]. It is for this reason that one can argue that absence of electrical treeing performance review in the Cigré Brochure [22] can be regarded as a major omission. In the present paper the reproducibility of the rheology based material preparation technique is tested using electrical treeing measurements.

One of the reasons why nanodielectrics technology is still confined to laboratory environments is the challenges pertaining to achieving and validating uniform particle distribution and dispersion in the host matrix. Currently various microscopy examination techniques are used to evaluate dispersion and distribution of particles in different kinds of polymers (matrices), but these methods rely on the material being synthesised to completion first and furthermore can only provide information on the sample surface [11], [24]. Previous work explored use of rheology analysis techniques in determining the optimal nanoparticle loading level which in turn corresponds to the optimal particle dispersion in the host matrix [25]. This test was incorporated as a stage in the material preparation process which inherently improves the efficiency and reproducibility of the process.

Using carbon nanospheres and boron nitride as fillers in epoxy, this paper demonstrates the feasibility of using rheology tests in predetermining the optimal particle loading level validated through electrical tree, microscopy, and thermal conductivity tests. It is anticipated that with further developments this rheology-based nanodielectric material preparation process demonstrates a means of transferring the nanodielectric technology from the laboratory to industrial production.

The next section presents the methodology for developing the nanodielectrics. This is followed by experimental results and discussion on the electrical tree and thermal analyses. It is then highlighted how nanodielectrics can be a viable technology customised for applications in the context of Sub-Saharan Africa for sustainable power systems development.

2 Methodology

The two types of nanofillers used in this study are hexagonal Boron Nitride (BN) with a characteristic diameter of 80-90 nm (sourced from Xuzhou Jiechuang New Material Technology Co. Ltd.) and Carbon Nanospheres (CNS) with characteristic diameter of 80-180 nm (synthesised in the School of Chemistry at The University of the Witwatersrand). The host material used was a Bisephenol-A epoxy polymer matrix (Araldite Cy 231-1 and Aradur Hy 931 sourced from Huntsman). Epoxy is a versatile solid insulation material which finds many applications from low voltage electronics up to high voltage applications in the order of ~100 kV. In general, epoxy is obtained by combining two parts, a resin, and a hardener. Bisephenol-A epoxy is medium-high-voltage (MV) type of epoxy mainly used in 10-50 kV applications [25].

The materials were synthesised and tested with a Dispermat AE high shear mixer and RheolabQC (CC27/p4478 bob and C-CC27 cup) rheology measuring device. The nanoparticle loading level was then varied and rheological measurements taken for each. The rheology results indicated an optimal loading level of 1.09 vol % to 1.35 vol% for BN in Epoxy and 0.33 vol% for CNS in Epoxy. The samples were then taken through the full manufacturing procedure. Nine specimens were manufactured for electrical treeing tests and thermal measurements. The following subsections discuss the respective experimental procedures.

2.1 Electrical treeing test procedures

The samples comprised of a point-plane electrode geometry of 5 μm tip radius tungsten needle (Ogura Jewels™) cast in the insulation under test with an electrode gap of 3 mm. The entire electrode configuration was immersed in transformer oil. The electrical treeing activity was monitored through electrical tree partial discharge (PD) measurements using IEC 60270 with a 20 kV test voltage. The detailed description of the method is presented in a previous article by the authors [26]. The electrical tree PD parameters studied in this case were the phase-resolved-patterns (PDPRP).

PDPRPs have traditionally been used to characterise PD sources [27]. PDPRPs can also be used to identify the characteristics of new insulation properties like the effect of nanoparticles on the nature of electrical trees. As the electrical trees propagated in the insulation under continuous voltage application, the corresponding values of mean, maximum and minimum PD were recorded every second for the duration of the test. Simultaneously the PDPRPs for the entire life of the samples was taken as a video format recorded at a frame rate of 20 ms using Flashback Express recorder by Blueberry software [28]. The PDPRPs were sampled every 20 minutes from start to end. The first 300 minutes of PDPRPs for each sample batch are analysed in the present paper.

The following subsection gives information on the thermal sample methodology.

2.2 Thermal sample methodology

Two sample sets were required for the thermal conductivity and thermal expansion experiments. Cylindrical rods of the nanodielectrics with a diameter of 6 mm and length of 55 mm were prepared for the thermal expansion experiments.

An Orton Dilatometer LAA/002 was used to obtain the thermal expansion results. The sample was placed in a chamber surrounded by a furnace, the temperature of the furnace was increased at a rate of $1\,^{o}C/min$ from $0\,^{o}C$ until melting of the sample was detected. The first sample that was tested was the C/Epoxy samples until a temperature of 310 ^{o}C, at which point the sample began to melt and produce a significant amount of smoke. The pure epoxy and BN/Epoxy samples were then tested until a temperature of 250 ^{o}C to ensure that the samples would not melt.

Bulk cylindrical samples were prepared and sliced into cylindrical discs with a diameter of 20 mm and thickness of 2 mm. After slicing, was done the samples were surface conditioned (smoothed) using five stages of sandpaper polishing, sequentially the grain sizes started at 220 mm, 1200 µm, 9 µm, 3 µm, and ended with 1 µm. The surface conditioning was to ensure no sample surface unevenness was present during the experiments and to ensure constant thickness across the sample.

The principle operation of laser flash analysis (LFA) in accordance with ASTM E 1461 standard was used and implemented using a Flashline 3000. A PyroCeram sample was used as a standard reference to measure the thermal conductivity. The sample under test and the PyroCeram were placed in a chamber. First, a vacuum was pulled and then the chamber was filled with nitrogen gas. The chamber was then set at three predetermined temperatures, for this study the selected temperatures were cable joint operating temperatures of $100\,^{o}C$, $150\,^{o}C$ and $200\,^{o}C$.

A Xenon light source pulses three high intensity light flashes at the samples which is then measured by a detector kept in liquid nitrogen conditions. The thermal expansion and LFA analysis was done at the Council for Scientific and Industrial Research (CSIR) by Cermalab and results made available. The technique measures thermal diffusivity and then determines thermal conductivity and specific heat.

3 Experimental Results and Discussion

In this section the results of the PDPRPs, thermal expansion and thermal conductivity experiments are presented. Firstly, the following subsection gives the electrical tree results. The focus on the optimally loaded PDPRPs. The second subsection gives the thermal results.

3.1 Electrical tree PDPRP results.

Each set of the PDPRPs presented in this section comprises of screen shots each taken every 20 minutes during the initial 300-minute period from first 20 kV application. The images are arranged in a chronological order row by row from left to right as labelled in Figure 1. From Figure 1 for pure epoxy, the PDPRPs show a predominance of relatively small and erratic pulses which are characteristic of mainly bush-branch electrical tree types. For 0.33 vol% C/Epoxy however, the PRPRPs shown in Figure 2 indicate mainly branch type PDPRPs.

Figure 3 gives the 1.25 vol% BN/Epoxy sample PDPRP result. The magnitudes are significantly suppressed, not exceeding ~20 pC. The characteristics would typically be referred to as characteristic of bush type trees, but they could also be branch type trees with very small magnitudes.

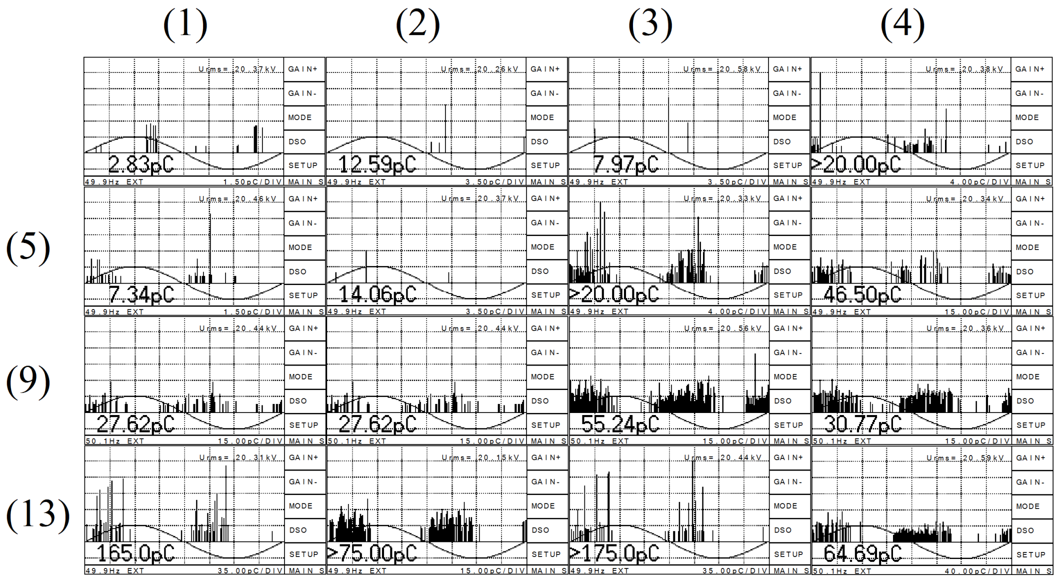

Figure 1: Clean epoxy PDPRP evolution showing single erratic pulses with increasing partial discharge magnitudes for the first four hours. The numbering convention is also shown.

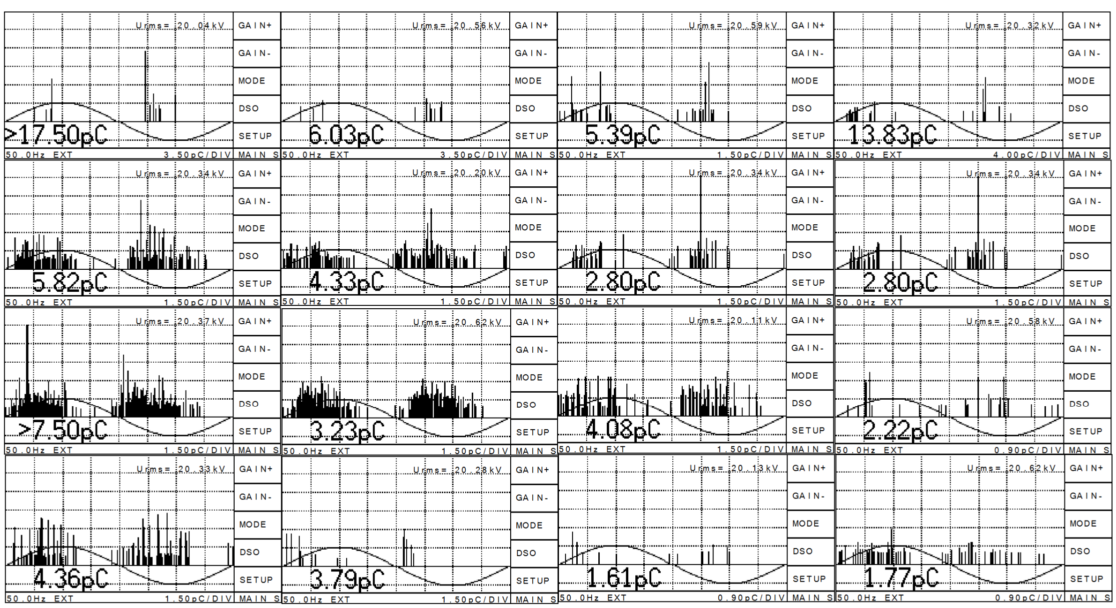

Figure 2: C/Epoxy 0.33 vol% showing predominantly small and quasi-uniform PD pulses a characteristic of bush tree types.

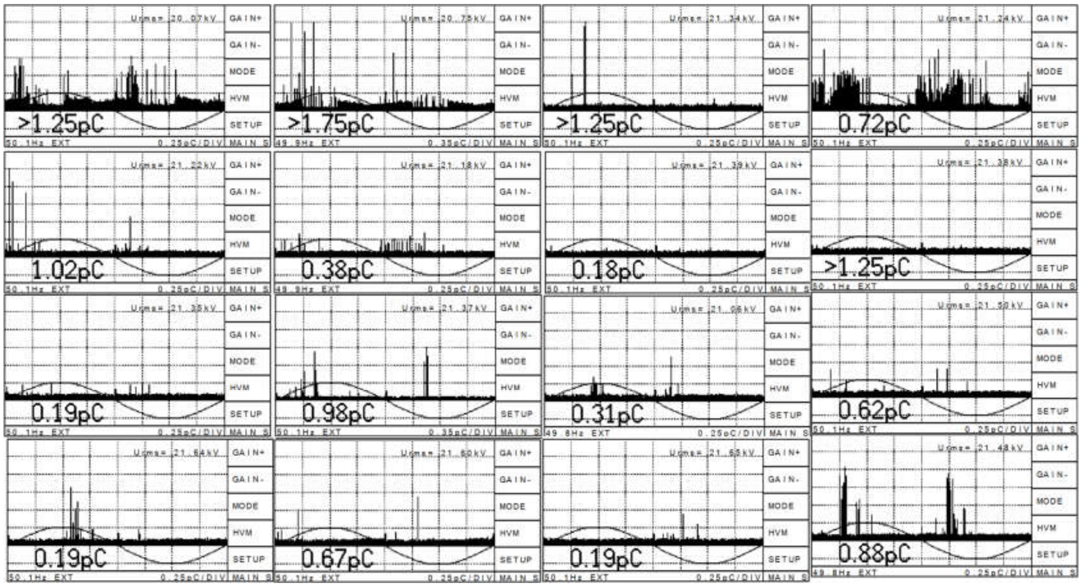

Figure 3: PDPRPs for BN/Epoxy 1.25 vol% for first four hours showing suppressed PD magnitudes with branch like characteristics.

Bush electrical trees support smaller and quasi-uniformly sized PD pulses while branches support bigger PDs of wide-ranging magnitudes. When continuously observed, electrical tree PDs occur as bursts and the composition of PD pulses in each half cycle of the excitation voltage change depending on how the electrical tree evolves in shape as it propagates in the insulation gap.

The PDPRP data along with other results previously presented by Hank et. al. [25], [26] show it can be concluded that 1.09 vol% -1.35 vol% for BN/Epoxy and 0.33 vol% C/Epoxy have the best characteristics with regard to suppressing electrical tree growth. These are achieved by limiting the PD magnitudes as seen in Figure 2 and Figure 3 when compared to Figure 1. The following subsection discusses the statistical analysis of the PD data.

3.2 Thermal experimental results

Figure 4 gives the thermal expansion results for pure epoxy, BN/Epoxy, and C/Epoxy nanodielectrics respectively. From Figure 4 the first observation is that all samples experience a thermal saturation point between $110\,^{o}C$ and $150\,^{o}C$. This saturation point is seen as a dip indicated in Figure 4. This dip indicates a phase transition related to the glass transition temperature of the epoxy as stated in the material data sheet to be in the $130\,^{o}C$ to $140\,^{o}C$ [29]. The epoxy moves from a crystalline structure (hard glassy material) to an amorphous (rubbery) structure by transitioning at the glass transition temperature. When the epoxy moves from crystalline to amorphous, the polymer chains and grain boundaries are broken and become disorderly [29]. Eventually the, epoxy begins burning and destruction of the sample is then observed at around $310\,^{o}C$.

The results show that the rate of expansion for the optimally loaded C/Epoxy is higher than BN/Epoxy and pure epoxy for the entire temperature range. Beyond the glass transition temperature, the pure epoxy has a rate of thermal expansion faster than the BN/Epoxy. However, the nanodielectrics maintain similar slopes before and after the glass transition as the pure epoxy. But when comparing the rate of thermal expansion (dilation) properties for both of the nanodielectrics, they have increased when compared to pure epoxy up until $80\,^{o}C$.

Within the glass transition temperature range, the dip observed with the pure epoxy is not as pronounced in the nanodielectrics. This is due to the nanoparticles which act as good thermal conductors. The heat transfer through the samples is relatively well maintained while the epoxy becomes amorphous.

The thermal expansion results indicate that both new materials are better at absorbing excess energy in certain temperature regions than the pure epoxy due to the addition of the nanoparticles, however, the C/Epoxy sample outperforms both samples. Table 1 gives the thermal conductivity and specific heat measurement results of the epoxy, BN/Epoxy, and C/Epoxy samples. At 100 °C, and 200 °C the thermal conductivities are lower than the pure epoxy.

For BN/Epoxy and C/Epoxy at 100 °C the thermal conductivity is lower than epoxy by 16.67 % and 40 % respectively. Similarly, the specific heat has decreased by 23 % and ~60 % for BN/Epoxy and C/Epoxy respectively. The decrease in specific heat indicates that the material should be able to transfer heat energy more easily as the thermal resistance has decreased.

At 150 °C there is a glass transition from the crystalline epoxy to amorphous epoxy as seen in Table 1. There is an increase in specific heat of ~190 % and ~30 % for BN/Epoxy and C/Epoxy respectively indicating that the thermal resistance has increased and thermal transfer should be more difficult. However, the thermal conductivity increases by ~180 % and ~105 % for BN/Epoxy and C/Epoxy respectively.

At 200 °C the specific heat has increased for BN/Epoxy and decreased for C/Epoxy by 31 % and 76 % respectively. While the thermal conductivity has decreased by 10 % and 70 % for BN/Epoxy and decreased for C/Epoxy respectively.

These results indicate that the nanodielectrics are complex systems with conduction mechanisms which are variable but most probably based on phonon scattering conduction mechanisms [29]. In developing the unified model, Tsekmas *et. al.* [30] showed that by increasing the particle concentration the thermal conductivity increased from 0.11 W/mK to 0.26 W/mK and 0.36 W/mK for surface conditioned hexagonal and cubic BN (5 vol%) respectively in the same type of epoxy at 20 °C. They showed that there was a correlation between increased particle concentrations and thermal conductivity.

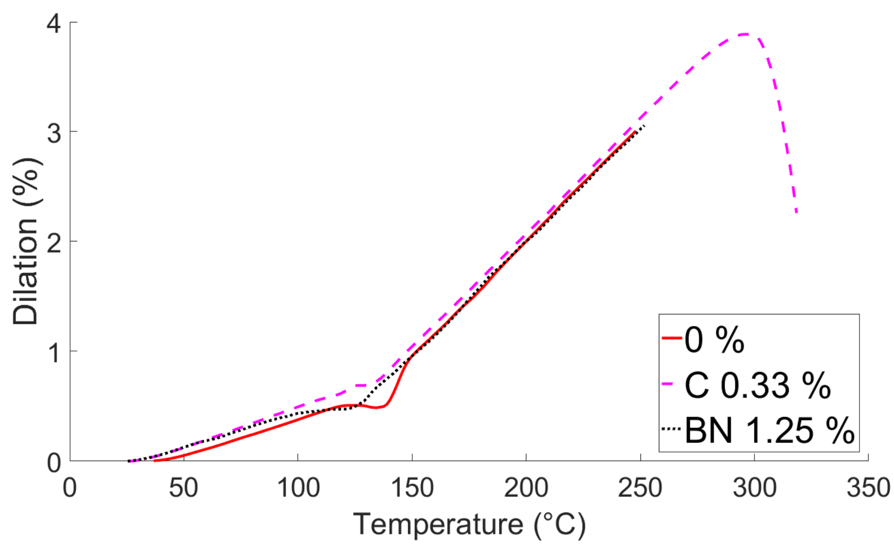

Figure 4: Thermal expansion results for epoxy, 0.33 vol% C/Epoxy and 1.09 vol% BN/Epoxy.

Table 1: Laser Flash Analysis measurement results for the epoxy and nanodielectric samples.

			Thermal Conductivity (W/(m K))		
Temperature	Pure Epoxy	BN/Epoxy	BN Change relative to pure epoxy (%)	C/Epoxy	CNS Change relative to pure epoxy (%)
100	0.3	0.25	-16.7	0.18	-40
150	0.2	0.48	182	0.35	106
200	0.4	0.36	-10	0.12	-70
			Specific Heat (J/(kg K))		
Temperature	Pure Epoxy	BN/ Epoxy	BN Change relative to pure epoxy (%)	C/Epoxy	CNS Change relative to pure epoxy (%)
100	2811	2164	-23	1141	-59
150	1823	5274	189	2389	31
200	3906	5101	31	949	-76
			Thermal Diffusivity (cm^2/sec)		
Temperature	Pure Epoxy	BN/ Epoxy	BN Change relative to pure epoxy (%)	C/Epoxy	CNS Change relative to pure epoxy (%)
100	0.0009	0.0009		0.0013	
150	0.0008	0.0007		0.0012	
200	0.0009	0.0006		0.0011	

The pure epoxy gives thermal conductivity of 0.3 W/(mK), 0.2 W/(mK) and 0.4 W/(mK) at 100 °C, 150 °C and 200 °C respectively. In the crystalline region, the thermal conductivity is relatively constant. At the glass transition there is a decrease in thermal conductivity and in the amorphous region, the thermal conductivity is higher than the crystalline region. The amorphous region is higher than the crystalline region because there is more kinetic energy in the disordered polymer chains assisting in the thermal transport with increased molecular vibrations.

The BN and CNS non-surface conditioned particles in epoxy respectively gave thermal conductivities of 0.48 W/mK and 0.35 W/mK. The thermal conductivities increase and peak at 150 °C within the glass transition temperature region before dropping down again. For the C/Epoxy, the thermal conductivity drops below the level of the crystalline region. But for the BN/Epoxy, both the specific heat and thermal conductivity in the amorphous region is higher than that of the crystalline region.

4 Conclusion

This paper has demonstrated that the optimal loading level of nanoparticle fillers in a host material can be relatively easily achieved through rheological analysis. Through the modified manufacturing process, optimal loading levels of carbon nanospheres in epoxy and boron nitride in epoxy dielectrics were determined. The resultant nanodielectrics show significantly superior ability to suppress electrical tree induced insulation degradation and this can be interpreted as a potential for longer life than conventional epoxy.

Furthermore, the thermal characteristics such as thermal conductivity are encouragingly better than the unfilled epoxy of 0.2 W/(mK) with 0.48 W/mK and 0.35 W/mK for BN/Epoxy and C/epoxy respectively. These findings give hope for the possibility of developing new insulation technology to meet the challenges of power network developments in the developing economies. As an example, operating a power cable with cable accessories or switchgear at

150 °C as opposed to 90°C would mitigate the currently prevalent overload related power network reliability problems in developing economies.

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