

NEW HVDC NANOCOMPOSITE ELECTRICAL INSULATION FOR IMPROVED MV AND HVAC PERFORMANCE

Nicola FREEBODY, Gary STEVENS
Gnosys Global Ltd– UK
n.freebody@gnosysgroup.com

Alun VAUGHAN
University of Southampton – UK
asv@ecs.soton.ac.uk

Fabrice PERROT, Andrew HYDE
GE Grid Solutions - UK
fabrice.perrott@alstom.com

ABSTRACT

This paper discusses the development of a new generation of HVDC nanocomposite electrical insulation materials for next generation HVDC technology which also confers improvement of electrical insulation performance for MVAC and HVAC systems.

INTRODUCTION

There is a need to develop reliable components for HVDC and HVAC transmission systems, such as post insulators, bushings and barriers, with controllable physical properties such as enhanced electrical breakdown and corona and discharge surface erosion resistance with low space charge formation and rapid charge decay and very low dc conductivity. Achieving this successfully while maintaining an appropriate balance of other key properties including mechanical and thermal properties and ageing behavior is of immense value to power equipment manufacturers and network operators that use this equipment. This is particularly important in the context of renewable generation integration and the move to develop Smart Grid and Low Carbon Networks. It is also important that the development to improve existing MV and HVAC networks that would benefit from more reliable materials and enable new MV and HV AC equipment designs to be realized that could improve asset performance and reduce asset footprint.

The paper seeks to translate current understanding and practical experience from the recent development of thermoset based nanocomposite electrical insulation materials and their use in insulator component manufacture following scaling of the materials to meet industrial production needs. Scalable processing methods were developed to produce components using materials with controlled dispersion and interfacial characteristics to achieve an appropriate balance between property and performance enhancements. This has been achieved for the specific nanocomposite materials developed in the NanocompEIM project within a materials design philosophy that is being generalised to a wide range of new cost effective insulating materials. This project benefitted from the support and involvement of the three UK transmission system operators who also have MV and HVAC asset interests.

Although the focus of the NanocompEIM project was on

HVDC applications, both the range of nanomaterials and the nature of the applications also has a positive impact on traditional HVAC applications. Some examples of future potential deployments include HVDC valve components, GIS equipment and barriers for AC and DC applications and substation composite post insulators.

NANODIELECTRICS

The dielectric, electrical and other physical properties of a material can be influenced and tailored by the inclusion of nanostructured materials to form a nanodielectric. For medium and high voltage insulators in HVAC and HVDC network applications, epoxy-based microfilled composites are widely used. Micron-sized particulates such as alumina and silica are commonly found in components and are used to reduce cost and drive the modification of the electrical, thermal and mechanical properties of the host resin [1]. Despite the improvement in thermal and mechanical properties, these micro sized particulates can have a negative impact on key electrical parameters such as electrical breakdown strength and space charge accumulation for HVDC applications. Additionally, for HVDC applications, high purity resins are required and so improvement via the addition of nanofillers must be matched by using an appropriate matrix.

The large specific surface area of nanoscale fillers and the many properties and performance factors linked to interfacial effects is a key feature of nanodielectrics. These interfacial effects include the characteristics of the regions between the nanofiller surface and the bulk matrix, known as the interphase region [2]. It is likely that properties not equivalent to the bulk matrix are adopted in this region and when the interfacial area is large, the proportion of interphase in the system will be commensurately large. In principle, the material is likely to exhibit unique combinations of properties thus attracting much technological interest in such systems.

The potential benefits of the nanophase in increasing resistance to surface corona and partial discharge [3], enhanced voltage endurance [4] and the potential mitigation of space charge formation [5] is discussed in a number of publications [6]. Tailoring of other properties such as permittivity, dielectric loss, thermal conductivity, dielectric strength, mechanical properties and thermal stability is also reported to be achievable. In order to achieve this balanced property enhancement however, the

nanoparticles must be well dispersed. Controlled dispersion of the nanophase and its qualification is central to this as is the understanding of nanophase surface chemistry and the interphase region between the nanofiller and the polymer matrix. This can be achieved by enhancing the interfacial coupling to the matrix and, as such the selection and control of appropriate surface chemistries is required. Reliable materials processing and industrial scaling of the process methods used is also essential. For this paper, scalable processing methods have been developed to produce components using materials with controlled dispersion and interfacial characteristics to achieve appropriate property and performance enhancements. This is illustrated alongside the need for balanced properties in regard to functionalized reactive and unreactive nano-fillers and their transfer to engineering practice.

Achieving this is of immense benefit to power equipment manufacturers and network operators that use this equipment, particularly in the context of renewable generation integration and the move to develop Smart Grid and Low Carbon Networks.

MATERIALS AND DISPERSION

Although others were tested, only the Huntsman CY1300 bisphenol A diglycidyl ether epoxy resin with the corresponding Huntsman Aradur A-917 anhydride hardener and 1-methylidiazole catalyst (available from Sigma Aldrich) is reported on here. A centrifugal planetary mixer operating at 3600 rpm for 3 min was used to disperse the nanofillers into the resin prior to curing and analysis. For cured samples the hardener and catalyst were then added, mixed via high shear mixing at 4000 rpm for 20 min, degassed, cured at 80 °C for 2 h and post cured at 120 °C. Cured samples were then cut to size and prepared in accordance with the methods appropriate to the analysis method.

Chemical dispersion and surface functionalisation of the nanoparticles have also been investigated in addition to mechanical dispersion via centrifugal planetary mixing. During centrifugal planetary mixing, high speed rotation combined with the counter revolution generates a large centrifugal force of up to 400g and establishes a vertical spiral convection mixing pattern that rapidly disperses the components uniformly. In the case of nanoparticle dispersion, during this mixing the particles collide with each other under high local shear force, assisting the breaking up of aggregates and agglomerates. It is important to ensure that the best dispersion of the nanofiller is achieved as significant agglomeration/aggregation of the nanofillers can lead to a decrease in the various final properties of the material.

Chemical functionalization helps to improve the interface between the host resin matrix and the nanoparticles.

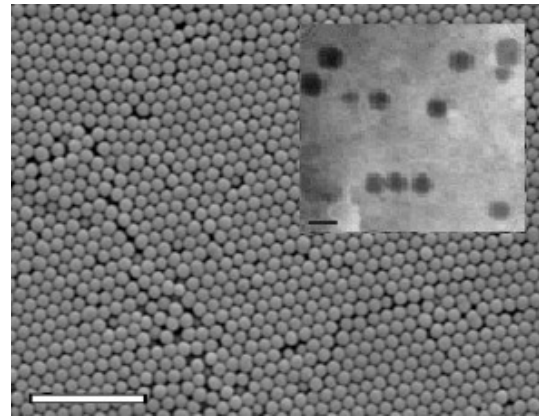


Figure 1. SEM image of epoxide functionalised nanosilica evaporated onto silica substrate, scale bar equivalent to 1 micron. Inset in top right corner is a comparison with TEM (scale bar = 100 nm).

Current literature suggests that the more closely bound the nanoparticles are to the host polymer matrix, the more stable it will be and the greater the improvement in macroscopic physical properties will be [2]. Two methods of chemical treatment which show clear benefit for use in HVDC and HVAC nanocomposites are reported here and compared to the commercially available Manopox filler dispersed in resin.

Method 1 uses (3-glycidioxypropyl)trimethoxysilane (GLYMO). This treatment was applied to a powdered nanosilica Method 2 is an epoxy functionalized, silane treated nanosilica (EFST) which was achieved in the liquid phase and was provided commercially and an example of which can be seen in the scanning electron microscopy (SEM) image and a transmission electron microscopy (TEM) image of the filler-epoxy composite can be seen in Figure 1. In these images it can be seen that the particles are well defined and stable with little or no aggregation occurring, previously identified as a potential cause for a reduction in electrical and mechanical physical properties.

All samples were incorporated into the CY1300 resin and the solvent from both chemical methods was extracted by rotary evaporation before the materials were mixed via planetary mixing. In all cases the results from untreated nanosilica (supplied by NanoAmor with an average particle size of 80 nm) and untreated boron nitride supplied by Momentive are compared to the chemically treated nanosilica fillers.

In this work scaling from typically 0.1 kg to tens of kilograms batch size was also demonstrated.

MATERIAL TESTING

Enhanced thermal conductivity, reduced electrical conductivity, an increase in electrical breakdown strength,

the mitigation of space charge, improved voltage endurance and the resistance to surface discharges are all desirable properties in dielectric materials intended for HVDC and HVAC applications. Electrical breakdown strength is, in particular, a useful metric when considering materials for use in HVAC applications and can help inform the failure probability of components in service, whereas measurements such as space charge accumulation and DC conductivity are more important in the consideration of HVDC components.

It is important to analyze any potential new nanocomposites for use in HVDC applications using methods relevant to those properties of relevance to the application so that component performance is accurately predicted. In addition to this it is essential to obtain a balance between properties when developing new materials. A significant increase in one property to the detriment of another does not result in a desirable material for component manufacture.

For this work, all samples were subject to a variety of thermal, electrical, mechanical, spectroscopic and optical measurements in order to check the dispersion of the nanofiller and overall resulting performance of the material. The advantage of performing all of these measurements is that a large body of knowledge can be built enabling us to better tailor the material to its specific use. By understanding property trade-offs for the materials in question, it will be possible to combine nanofillers and treatment methods such that balanced properties can be achieved and the material can be optimized for the application requirements.

With respect to the electrical properties such as breakdown strength (figure 2) and electrical conductivity (figure 3), it was found that nanosilica treated with either the GLYMO or the epoxide functionalized silane gave the best performance in comparison with the unfilled resin and

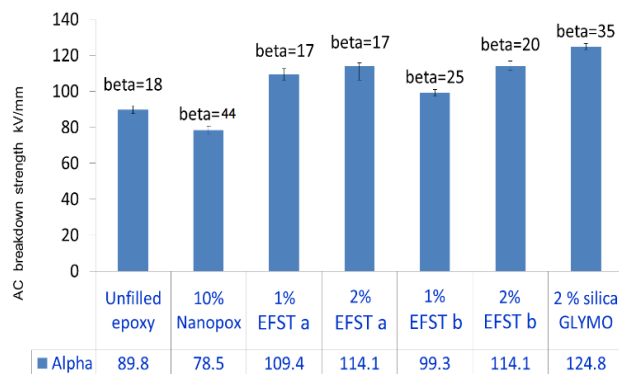


Figure 2. Average Alpha and Beta values from the Weibull analysis of electrical breakdown data of resin filled with treated nanosilicas.

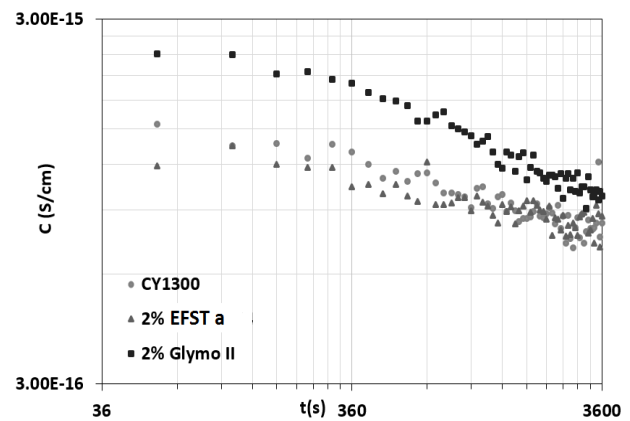


Figure 3. DC Conductivity plot of resin filled with treated nanosilicas.

untreated fillers, with no significant decrease in thermal conductivity or mechanical properties. Contrary to this, the Nanopox based composite yielded a decrease in electrical properties.

For all electrical measurements and nanofillers, it can be seen that there is an optimum filler loading where the electrical property enhancement increases up to a level of approximately 2% by weight of nanofiller, after which the properties begin to decrease again. This decrease is most likely caused by an increase in agglomeration after the optimum filler loading has been reached.

Samples were also subjected to thermal conductivity measurements and it was found that samples containing nano BN yielded a significantly higher thermal conductivity measurement without a resulting drop in electrical breakdown strength. This makes BN a strong contender for use in the electrical power applications and component manufacture. Currently, there is much work in this area and several research groups are working to utilize BN and maximize its effectiveness in this area.

COMPONENT MANUFACTURE

Nanocomposite post insulator and bushing components for comparative testing with micro composites were selected for the formation of demonstrator components according to the type of performance being required e.g. heat conduction, electrical breakdown or surface corona resistance.

Typically, HVAC and HVDC grid components contain micro fillers to ensure a match in the coefficient of thermal expansion between the resin and metal inserts. These microfillers are typically silica or alumina based microfillers depending on application. It is important to ensure that any addition of nanofillers into these systems does not adversely affect the properties of the micro fillers, whilst still yielding the desired property enhancement. All



Figure 4. Example demonstrator components cast from masterbatch nano-micro composite material formulations.

processes must also be scalable from the laboratory to potential use in industry if it is to be implemented and become business as usual.

This work culminated in the production of several nano/micro composite based materials which were master-batched to be suitable for the manufacture of MV components by conventional component casting companies using existing equipment and process methods. Scaled 5 kg master batches of selected materials containing functionalised nano/micro resin composites were produced. These master batches were then mixed and successfully cast via standard industrial casting procedures such as advanced pressure gelation and vacuum casting into demonstrator components by a component manufacturer, as can be seen in Figure 4. In both cases the production and finished components were successful with the first master batches produced. It was not necessary to refine the formulation.

The produced components were then subjected to detailed application testing including standardized measurements of thermal conductivity, voltage withstand tests, partial discharge evaluation tests, impulse testing and DC leakage current measurements were performed.

Comparative cantilever tests were conducted on the components made from master batches and the commercial benchmark epoxy system. The tests confirmed that all demonstrator components passed the standard 1kN for 1 minute test according to IEC60137 Edition 7 Section 8.9. Destructive cantilever comparative tests were also conducted and it was seen that the silica base nano/micro master batches yielded similar or improved performance over the benchmark.

Wet and dry voltage withstand tests were successful and were passed by all Post Insulators and Bushing

components tested. The partial discharge (PD) evaluation on the Post Insulators and Bushings showed relatively low levels of activity at power frequency withstand voltage levels with inception voltage well beyond their nominal voltages.

The DC leakage currents and thermal cycling tests revealed that even after 7 thermal cycles, all bushings tested showed no significant increases in DC leakage current; with levels below 1nA, except for the benchmark component. All showed levels well below the 100 nA fail criterion. This suggested very good integrity of all cast components. Dry lightning impulse voltage withstand tests were carried out at +/-75 kV without experiencing any internal or external flashovers.

CONCLUSIONS

All materials have been subjected to a wide array of physical property measurements. Properties such as permittivity, dielectric loss, thermal conductivity, dielectric strength, mechanical properties and thermal stability have all been investigated. Whilst all of these properties are necessary, the imperative is the important balance between these properties, essential for a successful material. With sufficient understanding of these properties, their trade-offs and process requirements it is possible to tailor material for specific use in HVAC or HVDC components.

Nanoparticle surface coupling or encapsulation will assist master batch stability. Modification of the interface between polymer and filler will also help to ensure good nanodispersion. Although many surface treatments assist dispersion, their use may not result in any improvement in electrical breakdown strength. In comparison, the use of GLYMO was able to achieve stable dispersions and an improvement in breakdown strength, as was the use of epoxide functionalized nanosilicas.

Processing with commercial planetary centrifugal mixers has been shown to be an effective method for nanoparticle dispersion and extending shelf life. It is a fast dispersion method that can be easily scaled to the 20 kg batch scale, which would suit fabrication of industrial scale quantities of master batch. The process naturally degasses the nanoparticle mixture and it is also possible to process in a vacuum. The method is well suited to highly viscous systems, i.e. naturally suiting epoxy resins and processing of systems with high solids content.

The production materials and components had properties that aligned with laboratory materials and the components fully satisfied conventional MV component acceptance tests. To ensure the technology can be commercialized, the opportunity now exists in a new development program (NanocompoEIM-II) to further optimize the material formulations and manufacturing process to take advantage

of the greater ease of processing and lower process energy required compared to existing materials, resulting in improved productivity and yield of defect free components. This will include an extended range of nanocomposite materials in addition to the production and critical testing of very large GIS insulators that are used in large numbers in power networks. These materials will then be made available for wider adoption

Acknowledgments

The Authors would like to thank and acknowledge the following for their contributions and financial support through the Ofgem approved Network Innovation Allowance scheme to this work: Gregory Tzemis (National Grid), Andrew Robertson (Scottish and Southern Energy), and David Walker (Scottish Power).

REFERENCES

- [1] T. Rouyre, A. C. Taylor, M. Fu, F. Perrot, I. James, 2010, "Nano- and micro-silica modification of epoxy polymers," *Proceedings IEEE International Conference on Solid Dielectrics*, pp.1-4
- [2] C. Yeung, 2013 "Spectroscopic analysis of nanodielectric interfaces." Doctoral Thesis, University of Southampton, pp. 223.
- [3] M. F. Frechette, R. Y. Larocque, M. Blouin, S. Boily, 2004 "Nanophase semi-conductive ceramics: dielectric surface performance when exposed to charges," *Proceedings Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp.326-331
- [4] J. K. Nelson and Y. Hu, 2005, "Nanocomposite dielectrics – properties and implications" *J. Phys. D: Appl. Phys.* Vol. 38 pp. 21
- [5] D. Fabiani, G. C. Montanari, A. Dardano, G. Guastavino, L. Testa, and M. Sangermano, 2008 "Space Charge Dynamics in Nanostructured Epoxy Resin," *Proceedings Annual Report Conference on Electrical Insulation and Dielectric Phenomena*, pp.710-713
- [6] T. Tanaka and A.S. Vaughan, 2017, *Tailoring of Nanodielectrics- from Fundamentals to Devices and Applications*, Pan Stanford Publishing, London, UK