Institution: University of Leicester

Unit of Assessment: 15 General Engineering

Title of case study: Dielectric Materials for HVAC and HVDC Electrical Power Transmission Components (Nanocomposite Insulating Materials)

1. Summary of the impact (indicative maximum 100 words)

Electrical power companies are tasked with operating a highly reliable and robust power system. Electrical power outages (blackouts) have serious consequences for the companies concerned as well as society. The health of electrical insulating materials is critical for the reliability of these systems as it often determines equipment lifetime.

Leicester was the first to demonstrate experimentally that polymer based nanocomposite materials could increase the service life and reliability of electrical insulation as used in high voltage power transmission systems. Its research has also led to the development of measurement techniques to assess the health and the extent of thermal ageing of HV power cables.

National Grid has used Leicester's research findings to manage and monitor its electricity transmission equipment, with resulting impacts on its safety, efficiency and financial economy. **Borealis**, a major international supplier of insulating materials has used the research to solve manufacturing problems and to set up test facilities for medium voltage cables. A Knowledge Transfer Partnership with **Alstom Grid** has led to the the establishment of a £1M commercial size HVDC cable test facility which has attracted £0.5M investment from **cable manufacturers worldwide**.

2. Underpinning research

The research in the High Voltage Laboratory at Leicester has focused on reliability issues and lifetime studies of the materials used as electrical insulators in components for high voltage alternating current (HVAC) and high voltage direct current (HVDC) applications. Key Leicester academic personnel: Prof. J.C.Fothergill (1984-2012, now Honorary Visiting Professor following a move to be Pro VC at City University) Prof. L.A.Dissado (1995- 2008, now Emeritus Professor) and a more recent academic appointment Dr S.J.Dodd (2007-).

Electrical insulation components are usually made from a polymer (such as epoxy resin or cross-linked polyethylene) in which micrometre sized mineral based filler particles (silica) are introduced to form a microcomposite. However, the incorporation of filler particles into a host polymer matrix results in materials that have decreased electrical properties such as electrical breakdown strength owing to the introduction of defects.

In 2002, under an EPSRC grant [**G1**], novel work at Leicester carried out by Fothergill and Dissado with W. Peasgood (RA, 2001-2004) and in collaboration with a visiting researcher, Prof. Keith Nelson (Rensselaer Polytechnic Institute, USA), led to the discovery that significant enhancement of the electrical properties of polymers could be achieved by the incorporation of nanometric sized solid particles of low volume fraction into the host polymer matrix to form a nanocomposite and was first publicised in CEIDP, the main rapid communication route for discoveries in the field of electrical insulation [**1**].

Although nanometric fillers (having dimensions of one-thousandth that of conventional micro-fillers) had been shown to improve the mechanical properties of polymers, this work showed for the first time that incorporation of nanometric fillers at low volume fraction produced fundamental changes in the way that electrical charge is stored within the polymer composite and therefore alters the macroscopic electrical properties and performance of the base polymer for both HVAC and HVDC applications. This research indicated that huge improvements in the lifetime of such nanocomposite insulation systems would be possible with the potential for large increases in the voltage withstand of insulator components. It was first published as a journal article in Nanotechnology [**2**]. This work has also led to a US patent no. US 7,884,149 B2 Nelson *et al*, on Nanostructured Dielectric Composite Materials, which claims considerable improvements in electrical insulation materials for AC or DC high voltage applications and references the Leicester work.

Leicester is at the forefront of research in materials for HVDC as evidenced by the work on materials for HVDC applications [**3**] and the invitation to Fothergill to give the invited keynote address “Ageing, Space Charge and Nanodielectrics: Ten Things We Don’t Know About Dielectrics“ at ICSD 2007, the leading IEEE sponsored European conference on materials for high voltage insulation. Leicester has demonstrated leadership through a EU Framework 5 grant [**G2**] in collaboration with a number of European utilities. Fothergill has also contributed a book chapter on nanodielectrics [**4**].

The quality of the work is recognised internationally, for example, by industry partners. Work with Schneider Electric [**G3**], France (electrical insulator manufacturer) has shown that interfacial moisture accounts for the observed dielectric behaviour in nanocomposites, (Fothergill, Dissado and PhD student Zou Chen [**5**]) and work sponsored by Borealis [**G4**], Norway, (a manufacturer of high grade polymers for HV power cables), demonstrated that the bulk electrical conductivity of polymeric insulation in HV cables could be used to assess the extent of thermal ageing of the insulating material, (Fothergill, Dissado, Dodd and PhD student T.Lau [**6**]).

Recently, a Knowledge Transfer Partnership (KTP), 2011-2012, in association with Alstom Grid [**G5**], has established a new unique £1M HVDC test facility at Stafford in the UK along with new strategic partnerships with a number of major international HVDC cable manufacturers, in particular Nexans, France, and Viscas, Japan. The KTP was awarded the highest grade of "Outstanding" by the KTP Grading Panel for its achievement in meeting KTP's Objectives.

3. References to the research

1. **‘**Towards an understanding of nanometric dielectrics**’,** Nelson, J. Keith; Fothergill, John C.; Dissado, L. A.; Peasgood, W., IEEE International Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), Annual Report, (2002), p 295-298.
2. **‘**Internal charge behaviour of nanocomposites’**,** Nelson, J.K. Fothergill, J.C., Nanotechnology, volume 15, issue 5, (2004) p 586 – 595. *This is the key paper relating to the discovery (157 citations* - Thomson Web of Science on 26th September 2013.**).**
3. **‘**Influence of thermal treatment and residues on space charge accumulation in XLPE for DC power cable application’**,** Fu, M.; Chen, G.; Dissado, L. A., Fothergill, J.C., IEEE Transactions on Dielectrics and Electrical Insulation, Volume: 14 Issue: 1 Pages: 53-64 DOI: 10.1109/TDEI.2007.302872 Published: FEB 2007.
4. **‘**Electrical Properties’**,** John Fothergill. Chapter in *Dielectric Polymer Nanocomposites***,** (ed. J K Nelson) Springer 2010, pp.197-228.
5. **‘**The effect of water absorption on the dielectric properties of epoxy nanocomposites Zou, Chen; Fothergill, J.C.; Rowe, S.W. IEEE Transactions on Dielectrics and Electrical Insulation, v 15, 2008, p 106-117. (50 citations).
6. **‘**The Measurement of Very Low Conductivity and Dielectric Loss in XLPE Cables: A Possible Method to Detect Degradation due to Thermal Aging’**,** J.C. Fothergill, T. Liu, S.J. Dodd, L.A. Dissado, U.H. Nilsson, IEEE Trans. Dielec. and Elec. Insul., 18(5):1544-1553, October 2011.

G1. Fothergill, J.C. and Dissado, L.A.: Nanocomposite Materials for Dielectric Structures, EPSRC: GR/R71788/01, £47,963, Jan – Jul 2002.
G2. Fothergill, J.C. et al, co-ordinator of the EU Framework 5 grant on “Benefits of HVDC Links in the European Power Electrical System and Improved HVDC Technology (HVDC)”, €1,694,434 = £1.16 million, 1/1/2003 - 30/6/2006.
G3. Fothergill, J.C. and Dissado L.A.: The Development of Nanocomposite Dielectric Structures, A joint proposal under the NSF/EPSRC request for cooperative activities in materials research between US and European investigators, EPSRC contribution £85,055 + €30,000 (=£20,500) from Schneider Electric, Jan 2004-Dec 2006, GR/S30672/01. Also: Fothergill, J. C. "Nanocomposites", Schneider Electric, €30,000, 2005 – 2007.
G4. Fothergill, J.C. and Dissado, L.A.: “Development of understanding of Insulation Ageing” Borealis AB, S-44486 Stenungsund, Sweden, 2006-2009, £35,000.
G5. Fothergill, J.C. and Dodd, S.J.: KTP between University of Leicester and Alstom Grid. Development of a HVDC Cable test facility at Alstom. KTP008177 £68,304 + £79,304 (company contribution), Jan 2011-Dec 2012

4. Details of the impact

Reliability of high voltage electrical insulators is of paramount concern to the electricity generation, transmission and distribution industries as failure of electrical equipment due to breakdown of the HV insulation leads to power outages (blackouts). The electricity industry needs to satisfy the demands of the Regulator (Ofgem) in terms of security of supply. Failure of HV power equipment, such as high voltage power cables capable of transporting all the power from a large power station (cost £0.3M per km), high voltage power transformers (cost £2-5M each), bushings and switchgear insulation, has significant financial penalties for the industry in terms of repair costs and fines imposed by the Regulator. These costs will ultimately have to be borne by UK business and domestic consumers in the form of increased energy costs [**A**]. The stakes are high: the typical cost of a 2GW HVDC link is of the order of *£1 Billion and the cost of failure can result in loss of ~£1M revenue per day due to lost electricity transmission alone.* 2GW also represents a significant fraction of the UK's generation capacity (~70GW) and could potentially cause power to be redirected through an already congested AC transmission network reducing network security. Reliability of electrical insulation is of major concern not only to electricity suppliers but also to HV equipment manufacturers whose products must be warranted against defects and failure over a 40-year operating time. The R&D Specialist, National Grid, states *"This research has provided the fundamental basis for many asset management decisions related to electricity transmission assets. The typical failure mechanism for high voltage assets is failure of the insulation and although not a frequent event, when it does happen is catastrophic leading to potential loss of supply, replacement of major assets and therefore increased costs (a single transformer for instance costs £2M-£5M). This research has provided knowledge on both the mechanisms but also on the potential for monitoring the health of the assets"* [**A**].

The research at Leicester on nanocomposites has informed industry in terms of new and improved electrical power products, research and development as evidenced by Leicester's contribution to "*Polymer Nanocomposites: Fundamentals and Possible Applications to Power Sectors"* published by CIGRÉ.(International Council on Large Electric Systems). CIGRÉ is one of the leading worldwide organizations on electric power systems, covering their technical, economic, environmental, organisational and regulatory aspects with aims to "facilitate the exchange of information between engineering personnel and specialists in all countries, to develop knowledge in power systems and to add value to the knowledge and information exchanged by synthesizing state-of-the-art world practices". The Senior Scientist at Hydro-Québec Research Institute, states *"The work of Fothergill and Nelson carried out in Leicester 2002-2004, on the electrical properties of nanodielectrics was the first experimental work designed to relate the presence of nano-sized additives in a polymer with its impact on dielectric properties. This work showed improved electrical performance of nanodielectrics over conventional microcomposite polymeric systems. These results have had a significant technical contribution to the CIGRE report on 'Polymer Nanocomposites: Fundamentals and Possible Applications to Power Sectors' which was first published in 2011, particularly the chapters in the report relating to electrical and space charge properties"* [**B**]. This document has substantial reach by demonstrating how nanocomposites could and are being usefully used by manufacturers and end users in the following HV systems: switchgear, DC power cables, enamelled wires, rotating machines, capacitors, all solid insulated substations, outdoor insulation and power electronics.

Polymers are the preferred choice for electrical insulation in electrical power cables and other HV power applications such as transformer bushings, cable terminations etc., as used on the electrical power transmission grid. The promise of improved electrical properties of polymeric based nanocomposites, *as first shown experimentally at Leicester*, has been embraced by a number of polymer manufacturers who supply the raw materials for insulation components. Borealis is probably the largest materials producer for polymers for the high voltage insulation industry in the world. They have been supporting many projects in the development of the incorporation of nanoparticles into their materials "both in internal projects and in external networks" [**C**]. Similarly, ABB have also invested in nanocomposite technology for their electrical insulation components [**D**]. Evonik Industries manufacture a range of epoxy based nanocomposite materials as master batches that are especially designed for electrical and electronic applications [**E**]. Similar products have been introduced for improved performance from manufacturers such as PMT Prepreg Resin systems and 3M. *"The Liu work project [G.4][6] had a clear impact as it demonstrated the use of dielectric spectroscopy as a tool for characterisation of insulating material. We (Borealis) have then proceeded to use Novocontrol equipment at Chalmers University in Gothenburg in order to solve various problems. The project gave also valuable knowledge in measurement techniques, knowledge that was utilised when setting up our system for tan delta measurement of medium voltage cables"*, Technical Manager, Borealis [**C**].

Leicester's recent involvement in a Knowledge Transfer Partnership (KTP), 2011-12, led to the creation of a new £1M HVDC cable test facility at Alstom Grid in the UK [**F**]. Alstom are a well-established engineering company who manufacture state-of-the-art HVDC converters for HVDC transmission systems. A DC transmission system offers a flexible and efficient means of electrical power transmission and represents a new international market for their products. This world-leading and unique long-term HVDC cable ageing evaluation centre, opened in 2012, combines three online measurement probes to characterise the electrical properties of commercial size 200kV cables whilst undergoing an industry standard programme of thermo-electrical ageing. This has raised Alstom's international profile as suppliers of HVDC systems and attracted considerable international interest from manufacturers and end users, such as National Grid, leveraged the establishment of industrial partnerships with international cable manufacturers such as Nexans (France) and Viscas (Japan) who have provided in-kind investment of £0.5M and each company has installed cables for long term ageing tests. The innivation has enhanced Alstom's profile as a world leader in HVDC technology and has enabled it to compete on the international stage with other HVDC technology suppliers, such as ABB and Siemens, who offer established turnkey solutions. "We are very keen for your research group to continue to support this key project to back-up the on-going work in Stafford to help us analyse and understand key ground breaking work associated with space–charge measurements in HVDC cables systems under VSC type converter stresses in years to come**.** *The expertise that your research group is able to provide our company with is very unique within the industry and has proven to produce real impacts*". Managing Director, ALSTOM Grid Research & Technology Centre [**F**].

5. Sources to corroborate the impact

[**A**] Email from R&D Specialist at National Grid, UK
[**B**] "Polymer Nanocomposites: Fundamentals and Possible Applications to Power Sectors" published by CIGRÉ (International Council on Large Electric Systems), Technical Brochure No 451, February 2011 and supporting email from Senior Scientist, Hydro-Québec Research Institute
[**C**] Email from Technical Manager, Borealis Group
[**D**] ABB Group, "Polymer nanocomposites as electrical insulation in high voltage applications", Presentation by Henrik Hillborg, Senior principal scientist, ABB Corporate Research, November 2010. http://download.ebooks6.com/Polymer-nanocomposites-as-electrical-insulation-in-high-voltage-download-w58261.pdf.
[**E**] NANOPOX® E Products, Technical Bulletin, Evonik Industries, www.evonik.com/hanse.
[**F**] Letter from Managing Director, ALSTOM Grid Research & Technology Centre