Institution:
University of Manchester

Unit of Assessment: UoA13b Electrical and Electronic Engineering

Title of case study: Application of environmentally friendly and fire-safe transformer liquids

1. Summary of the impact

Research on ester liquids (ELs) has proved they can be used in high-voltage (HV) transformers, bringing economic and safety advantages to the power industry and environmental benefits to society. Impact includes revisions to National Grid's oil policy recommending ester-filled HV transformers for use in London and the design and operation of the first 132kV "green" transformer (valued between £1m and £2m). The research has led directly to the creation of two international standards for professionals in global power utilities specifying the use of ELs in transformers. These developments have contributed directly to Manchester SME M&I Materials increasing sales from £15m (2008) to £29m (2012).

2. Underpinning research

The impact arises from research undertaken in Manchester from 2004 to date, with major publications from 2007 onwards. The key researchers were:

- Professor Zhongdong Wang (Lecturer 2000-2007, SL 2007-2009, Professor 2009-date)
- Dr Qiang Liu (PDRA 2011-2012, Lecturer 2012-date).

PhD students included Dr Dan Martin (2004-2008), Dr Imad Khan (2005-2009), Dr Jie Dai (2005-2009), Dr Xin Wang (2008-2011) and Dr Xiao Yi (2008-2012).

The aim of the research was to develop the electrical design criteria for ester-filled transformers; formulate an efficient method for impregnating the winding structure with ester liquids; and to understand the fault-diagnostic techniques required to design, manufacture and operate ester-filled HV transformers (HV refers to ≥ 132kV). Ester liquids have advantages over mineral oils in that they are biodegradable, both within soil and water, and they have a high flash-point, which makes them inherently safer, allowing a higher operating temperature.

The key research findings are as follows:

1. AC breakdown voltages of ester liquids under homogeneous fields were proved to be similar to those of mineral oil [1].

2. Key electrical characteristics, such as partial discharge inception, propagation and discharge patterns, under extreme inhomogeneous AC fields were determined and recommendations made for new and amended IEC standards related to electrical testing of insulating liquids [5].

3. The breakdown voltage-gap distance equations for ester liquids were formulated. This involved the measurement of breakdown and pre-breakdown phenomena under standard lightning impulses, and established fast streamer-led breakdown theory as the main cause of failure for long liquid gaps [2] and complex insulation geometries involving pressboard (solid insulation barriers used in transformers) [6].

4. Empirical equations were developed that linked liquid viscosity, temperature and vacuum level

with the processing time required for ester liquids to impregnate solid insulating materials [4].

5. Dissolved gas analysis for condition assessment was demonstrated to be appropriate for ester-filled transformers, although the gas amounts and types were modified [3].

3. References to the research

The research was published in the three most prestigious journals in the field of transformers and electrical insulation: *IEEE Transactions* on Dielectrics and Electrical Insulation*, IET Electric Power Applications* and *IEEE Electrical Insulation Magazine.* Paper [2] was cited by Dr Jan Hajek, Global Manager Basic Technology Development of ABB in his keynote address at the *IEEE International Conference on Dielectric Liquids*, Trondheim, 2011, as one of the two key liquid research breakthroughs in recent years.

Key Publications

[1] D. Martin and Z.D. Wang, "Statistical Analysis of the AC Breakdown Voltages of Ester based Transformer Oils", *IEEE Transactions on Dielectrics and Electrical Insulation*, 2008, Vol.15, No. 4, pp. 1044-1050 (Scopus citations = 21). DoI 10.1109/TDEI.2008.4591226

[2] Q. Liu and Z.D. Wang, "Streamer Characteristic and Breakdown in Synthetic and Natural Ester Transformer Liquids under Standard Lightning Impulse Voltage", *IEEE Transactions on Dielectrics and Electrical Insulation*, 2011, Vol.18, No.1, pp. 285-294 (Scopus citations = 18). DoI 10.1109/TDEI.2011.5704520

[3] I.U. Khan, Z.D. Wang, I. Cotton and S. Northcote, "Dissolved Gas Analysis of Alternative Fluids for Power Transformers", *IEEE Electrical Insulation Magazine*, vol.23, no5, pp. 5-14, 2007 (Scopus citations = 33). DoI 10.1109/MEI.2007.4318269

Other Publications

[4] J. Dai and Z.D. Wang, "A Comparison of the Impregnation of Cellulose Insulation by Ester and Mineral Oil", *IEEE Transactions on Dielectrics and Electrical Insulation*, Vol.15, No.2, pp.374-381, April 2008. (Scopus citations = 8) DoI 10.1109/TDEI.2008.4483455

[5] Z.D. Wang, Q. Liu, X. Wang, P. Jarman and G. Wilson, "Discussion on Possible Additions to IEC 60897 and IEC 61294 for Insulating Liquid Tests". *IET Electric Power Applications* 2011; 5(6): 486-493 (Scopus citations = 6). DoI 10.1049/iet-epa.2010.0209

[6] Q. Liu and Z.D. Wang, "Streamer Characteristic and Breakdown in Synthetic and Natural Ester Transformer Liquids with Pressboard Interface under Lightning Impulse Voltage", *IEEE Transactions on Dielectrics and Electrical Insulation*, 2011, Vol.18, No.6, pp. 1908-1917 (Scopus citations = 4). DoI 10.1109/TDEI.2011.6118629

4. Details of the Impact

Context

Fire and potential subsequent explosion is the major risk factor when operating high-voltage transformers in dense urban environments. Power transformers require insulating and cooling media, most commonly mineral oil an environmentally hazardous material which is also a fire risk. Ester liquids mitigate these hazards and risks, since they are biodegradable and their flash point is

350 °C versus 150 °C for mineral oil. Ester liquids have been used in low voltage (LV) transformers (≤33 kV) for twenty years, but were not used in HV transformers before 2008. The Manchester research established the performance of ester liquids under all the critical stresses of HV applications, which enabled the manufacture and operation of HV ester-filled transformers with environmental performance and fire-safety level expected by society.

Pathways to Impact

- The research team worked directly with sponsoring companies - M&I Materials, Alstom Grid, UK Power Networks (UKPN), National Grid, Scottish Power, Electricity Northwest and TJH2B (2005 to date).
- Technical papers were presented at leading international conferences in the field - IEEE: Conference on Electrical Insulation and Dielectric Phenomena (CEIDP), International Conference on Solid Dielectrics (ICSD), International Conference on Dielectric Liquids· (ICDL) and International Symposium on High Voltage Engineering (ISH).
- Presentations were regularly given to the Council on Large Electric Systems, (CIGRE) Session/Colloquium and working groups. CIGRE is the international association that develops professional practice guidance for engineers in the power system sector, and is the relevant technical council for the International Electrotechnical Commission (IEC).

All these activities increased the awareness of HV performance of ester liquids by the industry.

Reach and Significance of the Impact

1. Changes to international standards and professional practice. International standards in the electrical industry are established by the IEC. The research [5] highlighted the need for updates to existing IEC standards for the use of ester oils in HV transformers; these are currently being implemented by IEC Committee TC10 [a]. These standards are supported by professional practice guidance through CIGRE technical brochures which are the main practice guides for power engineers internationally. The results from the Manchester research are the basis of several sections in “Experiences in Service with Insulating Liquids" (2010) [f] and “DGA in Non-Mineral Oils and Load Tap Changers and Improved DGA Diagnosis Criteria” (2010) [g].

2. Ester liquid manufacturers: The research has enabled companies producing ester oils to expand their market from the small LV transformers that typically hold <100 litres to larger HV transformers that typically hold 40,000-80,000 litres of oil creating a 5.5m litre annual global market [h]. In the UK M&I materials, a high growth SME, and a sponsor of the research at Manchester, is using the research results to support sales of Midel 7131. Their Technical Manager stated “in doing this, customers and potential customers are persuaded of the advantages of using these alternative fluids... M&I Materials’ total sales increased from £15m in 2008 to £29m in 2012” [a].

3. Transformer manufacturers: The equations developed in [4] and [6] enabled manufacturers to design and manufacture ester-filled transformers. In 2008 Alstom Grid, the third largest transformer manufacturer in the world, became the first manufacturer in the UK to design and manufacture an ester liquid-filled 132kV/33kV/90MVA transformer. Such transformers are large capital items (typically valued at £1-2m) that are only manufactured to order and this first transformer was installed in EDF Energy’s network (see 4 below). Alstom Grid can now manufacture a sustainable range of green “eco-efficient” power transformers (10 to 200 MVA and up to 245kV) [e], and continue to use the Manchester research to help design a 400kV ester-filled transformer insulation model to validate this technology for the highest UK transmission voltages [b].

4. Distribution Utilities: Based on the statistical evidence in research output [1], EDF Energy (now UK Power Networks, the distribution utility for London) made a strategic decision to become the first utility to own and operate a "green" 132kV transformer using natural ester oils from renewable resources that are biodegradable and more fire resistant [d].

5. Transmission Utilities: National Grid, the UK power transmission system operator, has used the Manchester research to revise their oil policy to enable the use of ester oils to meet fire-safety concerns. National Grid has also ordered the first fire-safe 400kV transformer prototype with 20,000 litres of M&I Material Midel 7131, the liquid analysed at Manchester. The cost of each transformer is £1m-£2m [c].

The improved fire safety and environmental benefits of ester oils are driving change internationally and we are aware of anecdotal reports of US based utilities changing the oil type in existing transformers in high risk locations such as Disneyland.

5. Sources to corroborate the impact or benefit

a. Letter from Technical Manager, M&I Materials (CIGRE SC A2 WG A2.34 convenor) – demonstrating the impact of the research on the company's sales and the impact on international best practice.
b. Letter from Unit Managing Director, ALSTOM Grid Research & Technology Centre, Alstom Grid – supporting the technological impact on new products of manufacturer based in the UK
c. Letter from Technical Lead on Transformers, National Grid (IEC transformer chair) – confirming the safety impact of ester liquids on the UK transmission operator.
d. EDF Energy (now UKPN) on "green transformers" in 2008 – press release supporting the Manchester R&D involvement in the installation of the 1st green transformer.
e. Alstom Green Power Transformer Brochure – product brochure describing the range of "green" transformers incorporating ester oils.
f. "Experiences in Service with Insulating Liquids" (2010) – CIGRE brochure defining best practice using Manchester research results
g. "DGA in Non-Mineral Oils and Load Tap Changers and Improved DGA Diagnosis Criteria" (2010) – CIGRE brochure defining best practice using Manchester research results
h. Transforming the Transformer Industry, inform August 2008 – a paper informing the size of global market for ester liquids