Institution: University of Manchester

Unit of Assessment: 12 (Engineering)

Title of case study: Reducing usage of fossil-oil-based insulating liquids in power transformers to deliver environmental, safety, and financial benefits.

Period when the underpinning research was undertaken: 2004 – 2020

Details of staff conducting the underpinning research from the submitting unit:

Name(s):	Role(s) (e.g. job title):	Period(s) employed by submitting HEI:
Dr Qiang Liu	Reader 2019 – to date, Senior Lecturer 2016 – 2019, Lecturer 2012 – 2016	2012 – present
Professor Zongdong Wang	Professor 2009 – 2020, Senior Lecturer 2007 – 2009, Lecturer 2000 – 2007	2000 – 2020
Dr Shanika Matharage	Experimental Officer 2018 – 2020 PDRA 2016 – 2018	2016 – 2020
Professor Paul Jarman	Professor 2019 – to date	2019 – present

Period when the claimed impact occurred: August 2013 – July 2020

Is this case study continued from a case study submitted in 2014? N

1. Summary of the impact

Research at The University of Manchester has improved the sustainability of the UK power industry by reducing the use of fossil-oil based insulating liquids (*i.e.* mineral oils) in power transformers. This has resulted in safer, greener and more reliable transformers with increased life span and minimised maintenance. These solutions include using biodegradable ester-based insulating liquids in new transformers, regenerating existing transformer mineral oils, and enabling the design, manufacture, testing and operation of high voltage ester-filled transformers in the National Grid. This has directly led to:

- increasing sales of ester liquids for M&I Materials [text removed for publication];
- improved sustainability of Electricity North West Ltd.'s distribution network by reducing the use of new fossil-oil based insulating liquids, leading to investment savings of GBP32,000,000 for the company;
- development of two international industry-regulating standards; and
- production of three technical brochures which are used globally as industry best practice guides.

2. Underpinning research

Since 2004, research at The University of Manchester (UoM) has sought to provide technical solutions to the industry-led challenge to reduce the use of mineral oils in transformers. The research sought to not only improve the sustainability of the electrical power industry, but also address the industry's needs for safer and more reliable power transformers, with increased lifespans and minimised maintenance. The research addressed key technological challenges at nearly all stages of a transformer's life cycle. This includes at the design and development stage, such as characterising new materials or developing new design tools, and the stages of operation, condition monitoring and assessment, maintenance and life extension.

Key research findings include:

i. *Identifying the characteristics of ester liquids that are required for design, manufacture and operation of more sustainable and safer ester-filled high voltage transformers*. The breakdown voltage-gap distance equations for ester liquids were formulated [1]. This involved measuring the 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 [1]. Empirical equations were developed that link

liquid viscosity, temperature and vacuum level with the processing time required for ester liquids to impregnate solid insulating materials in the factory [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 International Electrotechnical Commission (IEC) standards related to electrical testing of insulating liquids [3].

ii. *Developing Computational Fluid Dynamics (CFD) based thermal analysis methodologies for lowering down the hotspot factor (HSF).* HSF is the key factor to determine the highest temperature in a transformer and consequently a transformer's thermal lifetime. Experimentally validated CFD thermal modelling methodologies were developed that provided novel understanding about the thermal performance of ester-filled transformers under different operational scenarios [4]. Flow velocity, liquid types, and winding geometrical dimensions were systematically studied using dimensional analysis to support the CFD based thermal design principle for newly built transformers [4].

iii. *Developing more effective ageing indicators of transformers.* Detection methods for new ageing markers of methanol and ethanol in both conventional mineral oil and new ester liquids were developed [5]. Previous methods based on furan detection can only indicate late ageing status of cellulose paper insulation. The new methods are sensitive towards early life ageing process, which enabled an early diagnosis of high temperature issues and accurate prediction of thermal life [5].

iv. *Formulating mid-life oil regeneration regimes to manage and prolong transformer lifetimes.* This research developed mid-life oil regeneration regimes that could slow down the ageing process, therefore prolonging the lifetime of transformers. A two-stage based regeneration regime was proposed and trialled on a 77-year-old retired transformer [6]. The results proved that the second stage is necessary to improve the paper condition and hence to reduce the paper ageing rate. This releases the life extension potential for the sheer amount of distribution transformers.

3. References to the research

This body of work has produced over 70 academic publications, and is published in top journals in the field including *IEEE Transactions on Dielectrics and Electrical Insulation*, *IEEE Transactions on Power Delivery* and *IET Electric Power Applications and Energies*. Paper [1] was recognised in the keynote address at the IEEE International Conference on Dielectric Liquids, Trondheim, 2011, as one of the two key research breakthroughs for ester liquids. Citations are from Web of Science (December 2020).

[1] **Q. Liu** and **Z.D. Wang**, (2011) Streamer Characteristic and Breakdown in Synthetic and Natural Ester Transformer Liquids under Standard Lightning Impulse Voltage, *IEEE Transactions on Dielectrics and Electrical Insulation*, 18 (1): 285-294. DOI:10.1109/TDEI.2011.5704520 (120 citations)

[2] J. Dai and **Z.D. Wang**, (2008) A Comparison of the Impregnation of Cellulose Insulation by Ester and Mineral Oil, *IEEE Transactions on Dielectrics and Electrical Insulation*, 15 (2): 374-381, DOI: 10.1109/TDEI.2008.4483455 (24 citations)

[3] **Z.D. Wang, Q. Liu,** X. Wang, **P. Jarman** and G. Wilson (2011) Discussion on Possible Additions to IEC 60897 and IEC 61294 for Insulating Liquid Tests. *IET Electric Power Applications*, 5(6): 486-493, DOI 10.1049/iet-epa.2010.0209, (22 citations)

[4] X. Zhang, **Z.D. Wang,** and **Q. Liu,** (2017) Prediction of Pressure Drop and Flow Distribution in Disc Type Transformer Windings in an OD Cooling Mode, *IEEE Transactions on Power Delivery*, 32(4): 1655-1664, DOI:10.1109/TPWRD.2016.2557490, (12 citations)

[5] **S.Y. Matharage, Q. Liu**, and **Z.D. Wang**, (2016) Aging Assessment of Kraft Paper Insulation through Methanol in Oil Measurement, *IEEE Transactions on Dielectric and Electrical Insulation*, 23(3): 1589-1596, DOI: 10.1109/TDEI.2016.005564 (34 citations)

[6] **Q. Liu**, R Venkatasubramanian, **S. Matharage** and **Z.D. Wang**, (2019) Effect of Oil Regeneration on Improving Paper Conditions in a Distribution Transformer, *Energies*, 12(9): 1665, DOI: 10.3390/en12091665, (1 citation)

4. Details of the impact

Context

Transformers are crucial for the transmission and distribution of high voltage electricity. They are traditionally filled with fossil-oil-based insulating liquids, *i.e.* mineral oil, which acts as a dielectric, a cooling medium and a vector for ageing and fault diagnostic markers. This type of oil is both an environmental pollutant, and poses a substantial fire risk should the transformer malfunction or overheat (as a flammable liquid with a low flash point of 150 °C). Ester liquids remain safe up to a flash point of 350 °C. Compared to traditional mineral oils, ester liquids provide better fire safety performance, and are biodegradable, therefore posing less environmental risk. Yet, their higher viscosity can reduce their cooling performance.

For mineral oil-filled transformers currently in operation, it is important to prolong their lifetime without reducing their reliability, and this requires an oil-regeneration process that minimises ageing and improves transformer health. This will defer investment in replacing existing transformers, and overall reduce the use of mineral oils.

Pathways to impact

The underpinning research [1-6] was funded through the industry-sponsored Transformer Research Consortium (TRC) projects, as well as the Innovation Funding Incentive (IFI) from Ofgem (the UK government regulator for gas and electricity markets).

The TRC was established by Wang in 2005 at UoM. It has obtained funding from national and international companies and research bodies who have directly informed the research need. This has involved four phases, with different companies sponsoring the UoM research:

Phase 1, 2005-2007	GBP200,000	Sponsored by Alstom, Electricity Northwest, M&I Materials, National Grid, Scottish Power, TJH2B and UK Power Networks
Phase 2, 2008-2011	GBP400,000	Sponsored by Alstom, M&I Materials, National Grid, Scottish Power, TJH2B and UK Power Networks
Phase 3, 2012-2016	GBP1,000,000	Sponsored by Alstom, M&I Materials, National Grid, Shell, Scottish Power, TJH2B, UK Power Networks and Weidmman;
Phase 4, 2017-2021	GBP1,400,000	Sponsored by Cargill, EPRI, M&I Materials, National Grid, Shell, SGB-SMIT, Scottish Power, TJH2B and Weidmman

Invited keynotes and presentations, based on [4] and [5], were delivered at industry-focused workshops at EuroTechCon (2014) and EuroDoble (2016) as well as the world's largest transformer manufacturing event - CWIEME Berlin – in 2018. This enabled new companies to learn about the research activities and join the Consortium.

The research team has also contributed, through technical papers, to global sessions organised by the Council on Large Electric Systems (CIGRE) in 2016 and 2018. Both papers were awarded the best papers within the transformer study committee. 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). Both government and industrial bodies attend this annual event.

Reach and significance of the impact

Enabling an environmentally friendly and fire-safe ester liquid to be used in the high-voltage transformer market

UoM research has contributed throughout the development process of environmentally friendly and fire-safe ester liquids in high voltage transformers from Technical Readiness Level 2 (TRL - the maturity of a technology) [1, 4] to TRL 9 [2, 3] [A]. M&I materials, a high-growth SME and key sponsor of the research, is using the research [1-5] to support exports of their main product, MIDEL 7131. Based on UoM research, M&I Materials have taken MIDEL 7131 from a niche product to significant use in high voltage transformers, and have consequently experienced substantial growth in this market. Their Technical Manager stated, "*The success of this business is due in no small part to the ongoing relationship between the company and the TRC*" [B]. [Text removed for publication].

Application of ester-liquid transformers and best-practice into the electricity power network

The research enabled the pioneering use of MIDEL 7131, a synthetic ester liquid, in transformers at a new 400 kV substation in London [C]. Following the UoM research that showed MIDEL 7131 esters were suitable for HV transformers, the National Grid and their development partner, Siemens, were able to develop a safer, more compact high voltage transformer design using the synthetic ester, which significantly contributed to an overall site reduction of 40% compared with a conventional substation [D]. [Text removed for publication]. The higher flashpoint of MIDEL 7131 enables the transformers to be '*in closer confines*' [C], which makes them suitable for high density urban areas, whilst remaining safe to the local community. Other UK utility operators, such as the Scottish Power Energy Network, have since followed, replacing mineral oils in high-voltage power transformers with ester liquids [E].

The research [1-5] has been used by eight CIGRE and IEC working groups (IEC 2, CIGRE 6) to inform several technical brochures and standards, recognised by power engineers globally. These have then led to the production of best practice guides, promoting the global use of ester-filled transformers [F, G], including:

- CIGRE Technical Brochure 741 "Moisture measurement and assessment in transformer insulation" (2018);
- CIGRE Technical Brochure 779 "Experience with transformer solid insulation ageing markers" (2019);
- CIGRE Technical Brochure 761 "Condition assessment of power transformers" (2019);
- IEC 62975 standard (pre-released version 2020) "Natural esters – Guidelines for maintenance and use in electrical equipment"; and
- Maintenance and Revision of IEC 60076-2 standard "Power Transformers: Temperature Rise".

Improving industry applications of transformer thermal modelling techniques

The transformer thermal modelling methodologies developed in [4] have changed the industry's understanding of existing thermal design tools. This research established CFD-based dimensional analysis methods, which have identified issues with existing techniques used by transformer manufacturers when promoting their designs. [Text removed for publication].

Improving transformer ageing indicator processes and oil regeneration methods for better network management and reduced network investment

The research on methanol measurement in conventional mineral oils and alternative liquids promoted the application of a novel transformer-ageing indicator [5]. New ageing markers

have provided the necessary additional information to effectively manage the ageing transformer fleet and understand the impact of changing load patterns in the network. The work has directly fed into the CIGRE working group A2.D1.46 [F.ii] and IEC working group PT63025, which underpinned the international standard developed in 2020 on measuring methanol in transformer liquids [D]. The UoM group is the first research group in UK to develop this method, and in 2018, the knowledge and skills transferred to two commercial oil analysis labs in the UK, *i.e.* TJH2B (TRC phase 4 sponsor) and SGS (the oil test provider for National Grid) [D]. As a result, National Grid has adopted this measurement across their fleet of power transformers [D].

The research-led development of a two-stage oil regeneration regime [6] has been incorporated by ENWL(Electricity North West Ltd) as 'business as usual' [H]. Deferring the investment on new transformers effectively reduces the usage of mineral oils. As confirmed by M&I Materials, "e*xtension of asset life, by even 20%, implies significant cost benefits to the utilities who are the end users…as the average cost of transformer replacement varies from several thousand pounds to several hundred thousand pounds*" [B].

ENWL has rolled out the two-stage oil regeneration technique and confirmed that "*the technique offered the greatest opportunity to improve the transformer's health index and thereby extended the operational life of the transformer*", and has resulted in financial benefits of "*around GBP32,000,000 savings from deferred transformer replacement in RIIO-ED1*" - RIIO-ED1 is the first electricity distribution price control period (2015 to 2023) [H]. Oil regeneration is being implemented by ENWL: across the 13 mid-life transformer sites at which this is currently deployed, ENWL have estimated that extending transformer life *via* oil regeneration, has generated savings of approximately GBP15,000,000 in RIIO-ED2 (2023 – 2028) [H].

5. Sources to corroborate the impact

[A] Presentation by National Grid at the Low Carbon Network Conference 2015 "*10-year timeline of ester liquids research*".
[B] Letter from Technical Manager, M&I Materials (March 2020)
[C] Press release – "National Grid London 400/132 kV 240 MVA MIDLE transformer" (May 2015)
[D] Letter from Head of Innovation, National Grid (April 2020)
[E] Publication authored by Scottish Power Energy Network confirming SPEN's use of ester-filled transformers, and attributing to UoM research.
S. Tee, D. Walker and M. Bebbington, "Experience of Synthetic Ester Filled Transformers in SP Energy Networks," *2019 IEEE 20th International Conference on Dielectric Liquids (ICDL)*, Italy, 2019, pp. 1-4, doi:10.1109/ICDL.2019.8796812.
[F] CIGRE Technical Brochures – three technical brochures including:
F.i - 741 "Moisture measurement and assessment in transformer insulation" (2018)
F.ii - 779 "Experience with transformer solid insulation ageing markers" (2019)
F.iii - 761 "Condition assessment of power transformers" (2019)
[G] IEC standards – two standards including:
G.i - IEC MT 60076-2: "TC 14Power Transformers: Temperature Rise"
G.ii - IEC 62975 standard (pre-released version 2020) "Natural esters – Guidelines for maintenance and use in electrical equipment"
[H] ENWL Innovation Strategy 2018