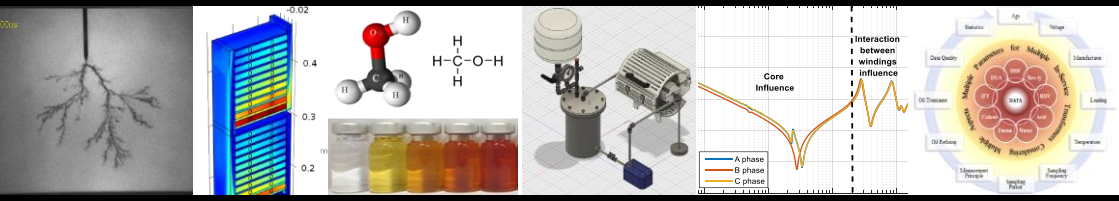
MANCHESTER 1824

The University of Manchester



Transformer Research at Manchester

2019

Contents

Transformer@manchester.ac.uk

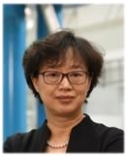
1. Overview

Transformer research at The University of Manchester (formerly UMIST) has been actively growing under the leadership of Prof. Zhongdong Wang since the beginning of the 21st century. The research team now comprises 3 academic staff, Prof. Wang, Prof. Paul Jarman, Dr. Qiang Liu, 3 to 5 post-doctoral research associates and 12 to 15 PhD students. The expertise on transformer research extends from understanding the fundamental electrical breakdown and thermal degradation mechanisms through design and modelling to condition assessment, asset management and data mining. The team has extensive experimental and modelling experience in research topics including discharge and breakdown, thermal performance, insulation ageing assessment, dissolved gas analysis, frequency response analysis, asset management, electromagnetics and digital twins.

The research has been supported by a £10m funding portfolio from the UK research council and national and international industrial companies. The team has published 70+ journal papers and 180+ conference papers. PhD students have received several best student paper and young researcher awards from international conferences. With the international recognition of transformer liquid research at Manchester, the 19th IEEE International Conference on Dielectric Liquids (ICDL) was held at The University of Manchester in 2017. The team members have contributed to 12 CIGRE working groups and 8 IEC standard working groups. The research on environmentally friendly and fire-safe ester transformer liquids from Technology Readiness Level (TRL) 2 to 9 enabled the pioneering use of synthetic ester liquid in transformers at a new 400 kV substation in London. These are the first 400kV synthetic-ester-filled transformers in the world, built by Siemens and installed by National Grid in 2017 utilising the fire and environmental benefits that are required to integrate a 3x240MVA transformer substation on a very small urban site efficiently within the local community.

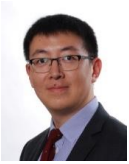
Moving forward, we are looking to promote research collaborations with top universities and leading companies and we are keen to recruit talented researchers. Together we can deliver fundamental and engineering research to shape the future of transformer industry.

2. Research Team



Prof. Zhongdong Wang (SMIEEE, MIET)
Zhongdong received the B.Eng. and the M.Eng. degrees in high voltage engineering from Tsinghua University in China in 1991 and 1993, respectively and the Ph.D. degree in electrical engineering from UMIST in 1999. Currently she is a Professor of High Voltage Engineering at the Department of Electrical and Electronic Engineering, Associate Dean for Internationalisation in Faculty of Science and Engineering. She is specialised in transformer research.

Prof. Paul Jarman (CEng, MIET)
Paul graduated from Cambridge University in 1984 with an Honours degree in electrical science. He joined the Central Electricity Generating Board as a researcher and then National Grid as technical specialist for transformers. He was chair of IEC TC14. Currently he is a Professor of Electrical Power Equipment and Networks at the Department of Electrical and Electronic Engineering. He is specialised in asset management, equipment and power network interaction.



Dr. Qiang Liu (CEng, SMIEEE, MIET)
Qiang received the B.Eng. and the M.Eng. degrees in high voltage and electrical insulation from Xi'an Jiaotong University (XJTU) in China in 2005 and 2008, respectively and the Ph.D. degree in electrical power engineering from The University of Manchester in 2011. Currently he is a Reader in Power System Plant at the Department of Electrical and Electronic Engineering. He is specialised in insulating liquids and their applications in high voltage equipment.

Dr. Shanika Matharage	PhD 2013-16; PDRA 2016-19; EO 2019-	Ageing assessment
Dr. Xiang Zhang	PhD 2014-2017, PDRA 2017-	Thermal modelling
Dr. Yiming Huang	PhD 2015-2019, PDRA 2019-	Partial discharge
Xiaozhou Mao	PhD 2015-	FRA
James Hill	PhD 2016-	Bubble formation
Zong Wen Yan	PhD 2016-	Paper ageing indicators
Shuhang Shen	PhD 2016-	Streamer characterisation
Xiaohan Li	PhD 2016-	DGA
Donglin Liu	PhD 2017-	Streamer modelling
Berihu Mebrahtom	PhD 2017-	Dual-temperature ageing
Bozhi Cheng	PhD 2017-	FRA
Mingyu Han	PhD 2017	Traction transformer modelling
Sicheng Zhao	PhD 2018-	Thermal modelling
Thathsara Herath	PhD 2018-	Oil database analysis
Haichuan Yu	PhD 2018-	Breakdown testing
Yaoxian Yang	PhD 2019-	FRA
Abdelrahman Alshehawy	PhD 2019-	Space charge

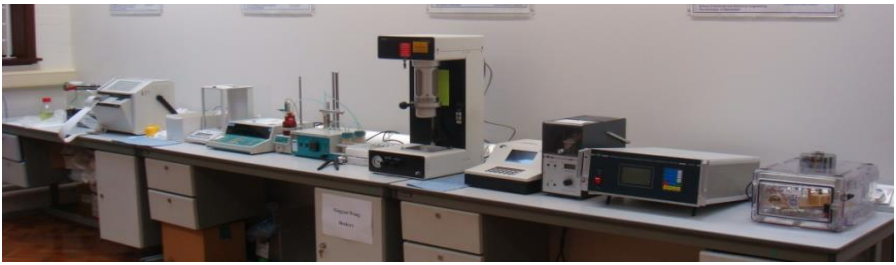
3. Research Facilities

The largest university-based high voltage laboratory is equipped with a full range of facilities that are capable of full scale electrical testing of high voltage equipment rated up to 400 kV.

- 2 MV Impulse Generator
- 800 kV AC Generator
- 600 kV DC Generator
- 800 kV Impulse Generator
- 300 kV DC Generator
- 10 kA High Current Source (20 kVA)

The dielectric materials laboratory is fully equipped with a wide range of facilities and instrumentations to pre-process, age and characterise the transformer liquid and solid insulation materials.

- Particle Image Velocimetry
- High Speed Camera
- Particle Counter
- Vacuum / air-circulating ovens
- FDS Analyser
- Dielectric Parameter Tester
- GC-MS-FID-TCD system
- HPLC system
- Karl Fischer Titrator
- Acidity Titrator
- Viscometer
- On-line DGA Monitors

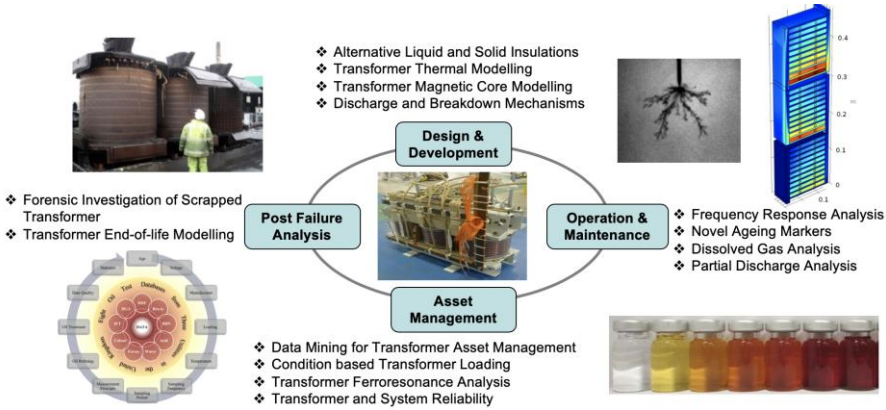


In addition to the experimental facilities, a range of specialist software and in-house developed programmes are hosted by two industrial computing work stations.

- COMSOL Multi-physics®
- SLIM
- MATLAB®
- ATP-EMTP, PSCAD™, PowerFactory
- Workstation (48 cores, 384 GB RAM)
- In-house developed programmes

4. Research Scope

The research scope covers the whole-lifecycle of a transformer from understanding the fundamental electrical breakdown and thermal degradation mechanisms through to improving condition assessment and asset management. This involves both experimental and modelling work on research topics including discharge and breakdown, thermal performance, insulation ageing assessment, dissolved gas analysis, frequency response analysis, asset management data analysis and digital twins.



Whole-lifecycle transformer research scope

4.1 Discharge and Breakdown

- Streamer characterisation under AC, DC and impulse (Shadowgraph/Schlieren based high-speed imaging)
- Creepage discharge and surface tracking along liquid-pressboard interface under various conditions
- Breakdown testing and mechanisms under different field configurations
- Interpretation of partial discharge
- Space charge measurement
- Modelling of streamer initiation and propagation

4.2 Thermal Performance

- Liquid flow characterisation in physical winding models (Particle Image Velocimetry)
- Computational Fluid Dynamics (CFD) based winding and radiator modelling
- Thermal hydraulic network modelling
- Dimensional analysis of effects of winding geometries and liquid properties on transformer thermal performance
- Interpretation and prediction of winding hotspot temperature
- Transformer real-time thermal rating

4.3 Insulation Ageing Assessment

- Accelerated thermal ageing of liquid-solid insulation based on single-temperature and dual-temperature cells

- Ageing mechanisms of cellulose-based paper insulation
- New thermal ageing indicators (Methanol and LMA)
- Partitioning and diffusion of ageing indicators in a transformer
- Oil regeneration
- Post-mortem analysis of scrapped transformers

4.4 Dissolved Gas Analysis

- Dissolved Gas Analysis (DGA) of liquids under laboratory simulated thermal faults using immersed heating and tube heating methods
- DGA of liquids under laboratory simulated electrical faults including partial discharge and spark breakdown
- DGA interpretation of alternative liquids
- Partitioning and diffusion of fault gases in a transformer
- Assessment of on-line DGA monitors

4.5 Frequency Response Analysis

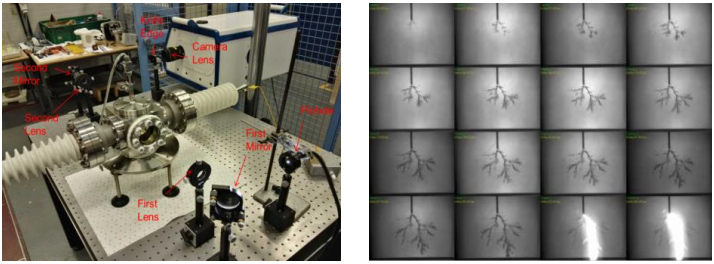
- Frequency Response Analysis (FRA) modelling
- Electromagnetic modelling of transformers to reproduce FRA results (White-box model)
- Interpretation of transformer FRA results in terms of winding deformation using models
- Identification of transformer design and winding structure from FRA
- Automatic classification methods for FRA results to aid asset management

4.6 Asset Management

- Deep understanding of transformer failure mechanisms and condition assessment techniques
- Statistical analysis and data mining of historical transformer failure and in-service condition monitoring data (DGA, FFA, Methanol, etc.)
- Thermal life estimation based on in-service observed ageing mechanisms and laboratory studies
- Transformer life and reliability models for use in system reliability studies

4.7 Digital Twin

- Geomagnetically Induced Currents (GIC), Ferroresonance, Inrush Current, Overfluxing, Very-fast Transient
- Thermal Loading / Overloading, Load Profile and Lifetime, Electromagnetic Field, Network Reliability

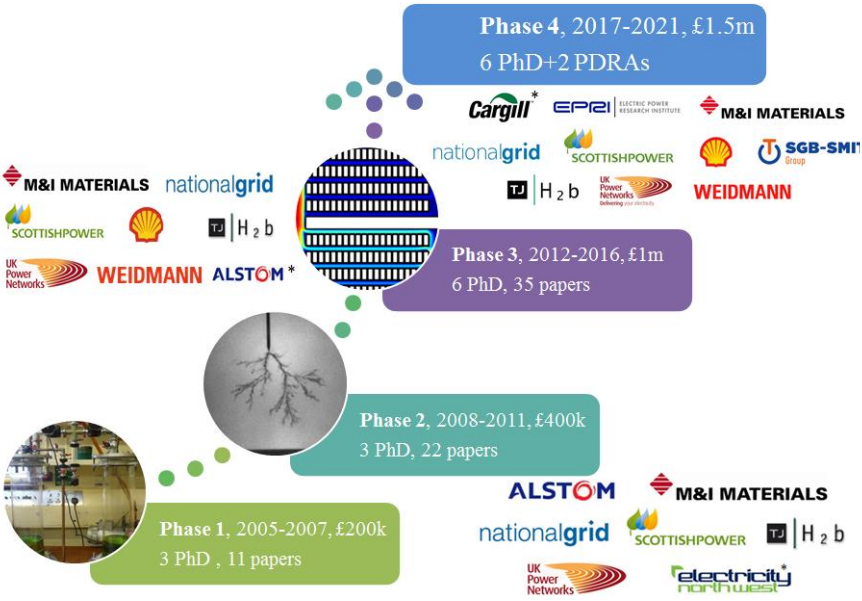


High-speed imaging study (left) experimental platform (right) streamer images

5. Research Project Highlights

The Transformer Research Consortium (TRC) was established in 2005 to develop knowledge and understanding related to many aspects of transformers, allowing optimisation of the design and operation of these important assets. In establishing a consortium, insight is gained from experts with a diverse specialist experience of transformer design and operation. The consortium brings together expertise from transformer manufacturers and owners, solid and liquid insulation material manufacturers and oil testing companies.

Phase 4 of the project is in part a continuation of the previous three phases. It is currently sponsored by the Electric Power Research Institute, M&I Materials, National Grid, SGB-SMIT, Shell Global Solutions, SP Energy Networks, and WEIDMANN Electrical Technology. Specifically, Phase 4 focuses on investigation into (not an exhaustive list): condition assessment; asset management; thermal modelling; and discharge and breakdown mechanisms. All with the overall aim of improving the efficiency and reliability of transformers.



History of Transformer Research Consortium

*Partial contribution.

6. Research Output - Publications

The team has published 70+ journal papers and 180+ conference papers with most of the journal papers published in IEEE and IET. Several selected publications are given below and an extended list of publications is given in Appendix A.

[1] Q. Liu and Z.D. Wang, “Streamer Characteristic and Breakdown in Synthetic and Natural Ester Transformer Liquids under Standard Lightning Impulse Voltage”, IEEE Trans. Dielectr. Electr. Insul., 18(01): 285-294, 2011.

[2] Z.D. Wang, J. Li and D.M. Sofian, “Interpretation of Transformer FRA Responses – Part I: Influence of Winding Structure”, IEEE Trans. Power Del., 24(2): 703-710, 2009

[3] J. Dai, Z.D. Wang and P. Jarman, “Creepage Discharge on Insulation Barriers in Aged Power Transformers”, IEEE Trans. Dielectr. Electr. Insul., 17(4): 1327-1335, 2010.

[4] H.-Z. Ding and Z.D. Wang, "On the Degradation Evolution Equations of Cellulose", Cellulose, 15(2): 205-224, 2008.

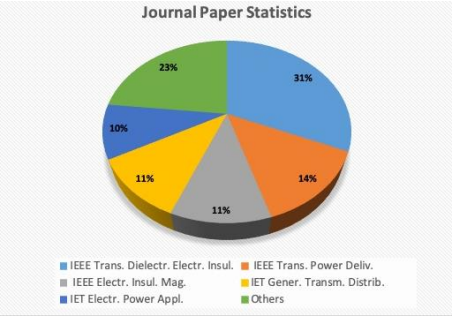
[5] C. A. Charalambous, Z.D. Wang, P. Jarman and M. Osborne, "2-D Finite-Element Electromagnetic Analysis of an Autotransformer Experiencing Ferroresonance", IEEE Trans. Power Deliv., 24(3): 1275-1283, 2009.

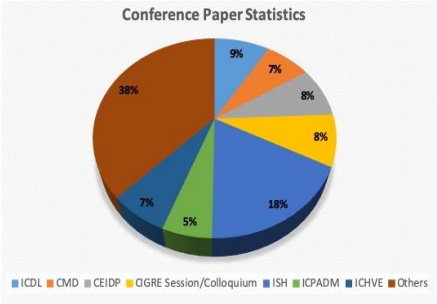
[6] S.Y. Matharage, Q. Liu, Z.D. Wang, G.Wilson and Ch. Krause, “Aging assessment of synthetic ester impregnated thermally non-upgraded kraft paper through chemical markers in oil”, IEEE Trans. Dielectr. Electr. Insul., 25(2): 507-515, 2018.

[7] X. Zhang, M. Daghrah, Z.D. Wang, Q. Liu, P. Jarman and M. Negro, "Experimental verification of dimensional analysis results on flow distribution and pressure drop for disc type windings in OD cooling modes," IEEE Trans. Power Del., 33(4): 1647-1656, 2018.

[8] Z. Liu, Q. Liu and Z.D. Wang, "Effect of electric field configuration on streamer and partial discharge phenomena in a hydrocarbon insulating liquid under AC stress", J. Phys. D-Appl. Phys., 49(18): 185501, 2016.

[9] Q. Liu, R. Venkatasubramanian, S. Y. Matharage and Z.D. Wang, "Effect of Oil Regeneration on Improving Paper Conditions in a Distribution Transformer", Energies, 12(9): 1665, 2019.





7. Research Output - Awards

EEIM (European Electrical Insulation Manufacturers) 'John Neal Award':

Shanika Matharage, 2018
Jie Dai, 2009

International Conference Student Awards:

ICDL 2019, Shuhang Shen, Roma, Italy
ICDL 2017, Zhou Mu, Manchester, UK
ICDL 2014, Wu Lu, Bled, Slovenia
CMD 2016, Xiang Zhang, Xi'an, China
CMD 2014, Bevan Patel, Jeju, South Korea
ICEMPE 2019, Xiaozhou Mao, Guangzhou, China
ICPADM 2018, James Hill, Xi'an, China

CIGRE Session, Colloquium, Conference Student Awards

NGN Competition 2016, Shengji Tee, Paris, France
ISH 2015, Xiongfei Wang, Pilsen, Czech Republic
A2 Colloquium 2009, Dahlina Sofian, South Africa

Regional Conference Colloquium Student Awards:

UPEC 2009, Swee Peng Ang, Glasgow, UK
EuroTechCon 2014, Xiongfei Wang, Warwickshire, UK
UHVnet 2019, Shuhang Shen, Manchester, UK
UHVnet 2017, Zong Wen Yan, Glasgow, UK
UHVnet 2016, Wu Lu, Cardiff, UK
UHVnet 2015, Muhammad Daghrah, Stafford, UK
UHVnet 2014, Shanika Matharage, Surrey, UK
IDCOMPU 2019, Xiang Zhang, Xi'an, China

Next Generation Researchers in Power Systems,

UoM representative 2017, ShengJi Tee, Beijing, China
UoM representative 2019, James Hill, Copenhagen, Denmark

CIGRE A2 Colloquium, South Africa, 2009

ICDL, Slovenia, 2014

8. Research Output - CIGRE and IEC

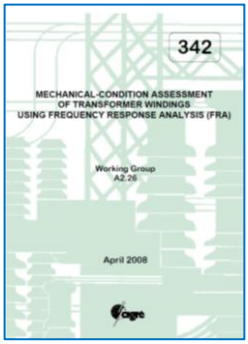
The research team has been actively contributed to 12 CIGRE working groups and 8 IEC working groups.

CIGRE

- A2.26 Mechanical condition assessment of transformer windings using FRA, Brochure 342
- A2.27 Recommendations for Condition Monitoring and Condition Assessment Facilities for Transformers, Brochure 343
- A2.34 Transformer Maintenance, Brochure 445
- A2.35 Experiences in service with new liquids, Brochure 436
- A2/C4.39 Electrical transient interaction between transformers and the power system, Brochure 577A
- A2/D1.46 Transformer solid insulation ageing markers
- A2.47 Condition assessment, Brochure 761
- A2.60 Dynamic thermal behaviour of power transformers
- A2.63 Transformer impulse testing
- D1.52 An evaluation of solid-state sensors and chemical methods, Brochure 741
- D1.68 Natural and synthetic esters - evaluation of the performance under fire and the impact on environment
- D1.70 Functional properties of modern insulating liquids for transformers and similar electrical equipment

IEC

- TC14/MT 60076-1 Power transformers – General
- TC14/MT 60076-2 Temperature Rise
- TC14/MT 60076-3 Dielectric tests
- TC14/MT 60076-5 Short Circuit Capability
- TC14/MT 60076-6 Reactors
- TC14/PT 60076-18 FRA
- TC14/WG 60076-57-1202 Phase-shifting transformers
- TC10/PT62975 Maintenance guidelines of natural ester insulating liquids



9. Research Output – Application

Application of environmentally friendly and fire-safe transformer liquids

Ester liquids have fire-safety and biodegradability characteristics superior to the mineral oils traditionally used in power transformers. Although used at lower voltages successfully for many years, their dielectric performance was not proven at transmission voltages. The research on ester liquids took the application from Technology Readiness Level (TRL) 2 (early investigation) to 9 (industrial application). The work underpinned the decision by National Grid to use synthetic ester liquid in three 240MVA transformers at a new 400 kV substation in London. The substation and the transformers were built by Siemens to fit into a very tight urban space and the low fire and environmental benefits were required to integrate the installation into the local community. This work has led the adoption of high voltage ester liquid filled power transformers by other utilities for example Scottish Power Energy Networks and Consolidated Edison.

The research over the past decade has produced 70 academic papers (25 journal and 45 conference papers) detailing the performances of ester liquids for many aspects. These publications, forming a critical mass in the literature, have been frequently cited, form a basis for advice on the design of ester filled transformers by global manufacturers and have promoted the global adoption of ester filled transformers at all voltages in particular in Brazil, India and China.

More information can be found:

https://www.eee.manchester.ac.uk/research/impact/high-voltage-transformers/

132 kV Natural Ester Filled Transformer, UKPN

400 kV Synthetic Ester Filled Transformer, National Grid

10. International Conference on Dielectric Liquids

The 19th IEEE International Conference on Dielectric Liquids (ICDL 2017) was held from 25 - 29 June 2017 at the University of Manchester. It was sponsored by IEEE and DEIS, supported by Baur, Cargill, M&I Materials, Shell and Wilson Power Solutions. ICDL 2017 provided a platform for 188 attendees from 24 countries including academics, researchers and industry experts to discuss properties, measurements, dielectric phenomena and applications of insulating liquids. Out of the 255 abstracts received, 151 full papers (from 24 countries) were accepted. Prof. Hitoshi Okubo delivered the prestigious Hans Tropper Memorial Lecture, with the title of “Kerr Electro-optic Electric Field Measurement and Electrical Insulation Performance in HVDC Liquid Dielectric Systems”.

ICDL 2017 Local Organising Committee

Zhongdong Wang (Chair)
Maks Babuder (Honorary Chair)
Qiang Liu (Technical Programme & Treasurer)
Shengji Tee (Secretary)
Shanika Matharage (Publication)
Xiang Zhang (Local Arrangements)

11. University Transformer Research Alliance

Overview

The University Transformer Research Alliance (UTRA) was established in 2019 by five nationally leading transformer research groups from the UK, Germany, Australia and China. The aim is to develop a strategy to advance transformer research in alignment with low-carbon energy requirements. It intends to work closely with the wider transformer community, including manufacturers, power utilities, materials providers, and test/service businesses to deliver fundamental and engineering research and to provide high quality postgraduate education/training of students and engineers. It seeks out opportunities where the community can work together and share the benefits of advanced transformer technology.

Vision

UTRA will enable university researchers to benefit from synergies in pursuit of advancement of knowledge in the areas of transformer related research, through:

- Research Leadership
- Strategic Research Direction and Guidance
- Engaging Stakeholders
- Recognising Young Talent

Objectives

UTRA will enlist a broad representation from global transformer research universities; providing up-to-date information on their research capabilities, which may include experience, expertise, and modelling, simulation and experimental laboratory facilities. UTRA will encourage the research community to provide a coherent view on the latest knowledge and the need for, the challenges in, and the direction of research. It will introduce state-of-the-art technologies and target improvements in efficiency. It also endeavours to strengthen industrial support for universities' research by showcasing qualities and competences.

The UTRA's Founding members include the following universities.

- The University of Manchester
- The University of Queensland
- Tsinghua University
- University of Stuttgart
- Xi'an Jiaotong University

UTRA Website: www.university-transformer-research.com

Acknowledgement

PhD and MPhil Graduates

Yufan Ni (PhD 2014-2018); Zhou Mu (PhD 2014-2018); Muhammad Daghrah (PhD 2014-2017); Xiang Zhang (PhD 2014-2017); Xiongfei Wang (PhD 2014-2017); Jing Xiang (PhD 2013-2017); Dongmiao Wang (PhD 2013-2017); Shanika Matharage (PhD 2013-2017); Zhao Liu (PhD 2012-2017); Shengji Tee (PhD 2012-2016); Wu Lu (PhD 2011-2015); Yuan Gao (PhD 2012-2015); Qi Tang (PhD 2011-2015); Bevan Patel (PhD 2010-2014); Dongyin Feng (PhD 2009-2013); Jinsheng Peng (PhD 2009-2013); Rui Zhang (PhD 2009-2012); Norhafiz Azis (PhD 2008-2012); Xiao Yi (PhD 2008-2012); Wei Wu (PhD 2008-2011); Qiang Liu (PhD 2008-2011); Xin Wang (PhD 2007-2011); Ang Swee Peng (PhD 2007-2010); Jie Dai (PhD 2006-2009); Mohd Taufiq Ishak (PhD 2006-2009); Imad Khan (PhD 2005-2008); Jie Li (PhD 2005-2008); Houssam Hajjar (PhD 2004-2007); Dan Martin (2004-2007); Dahlina Sofian (PhD 2003-2007); Qisti Ramli (PhD 2002-2007); Magdi Elborki (PhD 2000-2004); Sujeewa Hettiwatte (2000-2003); Ram Venkatasubramanian (MPhil 2013-2015); Sitao Li (MPhil 2010-2012); Aruna Gunatilake (MPhil 2003-2004)

Postdoctoral Research Associates (PDRA)

Shengji Tee (PDRA 2016-2018); Rafael Villarroel Rodriguez (PDRA 2015-2017); Wu Lu (PDRA 2015-2016); Bevan Patel (PDRA 2014-2016); Norhafiz Azis (PDRA 2012-2013); Xiao Yi (PDRA 2012-2013); Qiang Liu (PDRA 2011-2012); Yang Xu (PDRA 2009-2010); Charalambos Charalambous (PDRA 2005-2009); Hongzhi Ding (PDRA 2004-2008); Sugath Jayasinghe (PDRA 2002-2004)

Academic, Industrial and PhD Student Visitors

Yunpeng Liu (Acaemic Visitor 2013-2014); Wei Wang (Academic Visitor 2010-2010); Manjula Fernando (Academic Visitor 2006-2007); Jinsong Tao (Academic Visitor 2006-2007); Zhiqiang Meng (Academic Visitor 2004-2004); Jae Seung Park (Industrial Visitor 2013-2014); Hyun Joo Park (Industrial Visitor 2012-2012); Yuming Tu (Industrial Visitor 2001-2002); Baojia Han (Industrial Visitor 2000-2000); Lujia Wang (PhD Visitor 2018-2019); Xuwei Huang (PhD Visitor 2018-2019); Meng Huang (PhD Visitor 2015-2015); Rafael Villarroel Rodriguez (PhD Visitor 2014-2015); Yiming Zheng (PhD Visitor 2012-2013); Dan Zhou (PhD Visitor 2010-2012); Liang Zou (PhD Visitor 2009-2010); Ji Li (PhD Visitor 2007-2008)

Research Councils and Industrial Sponsors

Appendix. Selected Publications

[1] Y.M. Huang, Q. Liu and Z.D. Wang, "Effects of Temperature on Partial Discharges and Streamers in an Ester Liquid under AC Stress", IEEE Trans. Dielectr. Electr. Insul., 26(5): 1512-1519, 2019. (DOI: 10.1109/TDEI.2019.008131)

[2] M. Daghrah, Z.D. Wang, Q. Liu, A. Hilker and A. Gyore, "Experimental Study of the Influence of Different Liquids on the Transformer Cooling Performance", IEEE Trans. Power Deliv., 34(2): 588-595, 2019. (doi: 10.1109/TPWRD.2019.2895533)

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

[4] J. Hill, Z.D. Wang, Q. Liu, C. Krause and G. Wilson, "Analysing the power transformer temperature limitation for avoidance of bubble formation", High Volt., 2019. (doi: 10.1049/hve.2019.0034)

[5] J. Xiang, Q. Liu and Z.D. Wang, "Streamer characteristic and breakdown in a mineral oil and a synthetic ester liquid under DC voltage", IEEE Trans. Dielectr. Electr. Insul., 25(5): 1636-1643, 2018. (doi: 10.1109/TDEI.2018.006938)

[6] S. Y. Matharage, Q. Liu, Z.D. Wang, G. Wilson and C. Krause, "Aging assessment of synthetic ester impregnated thermally non-upgraded kraft paper through chemical markers in oil", IEEE Trans. Dielectr. Electr. Insul., 25(2): 507-515, 2018. (doi: 10.1109/TDEI.2018.006833)

[7] X. Zhang, Z.D. Wang, Q. Liu, P. Jarman and M. Negro, "Numerical investigation of oil flow and temperature distributions for ON transformer windings", Appl. Therm. Eng., 130: 1-9, 2018. (doi: 10.1016/j.applthermaleng.2017.10.092)

[8] X. Zhang, M. Daghrah, Z.D. Wang, Q. Liu, P. Jarman and M. Negro, "Experimental Verification of Dimensional Analysis Results on Flow Distribution and Pressure Drop for Disc-Type Windings in OD Cooling Modes", IEEE Trans. Power Deliv., 33(4): 1647-1656, 2018. (doi: 10.1109/TPWRD.2017.2739483)

[9] D. Wang, S. J. Tee, Q. Liu and Z.D. Wang, "Factorial analysis for ageing assessment of in-service transformers", IET Gener. Transm. Distrib., 12(13): 3177-3185, 2018. (doi: 10.1049/iet-gtd.2017.1531)

[10] X.F. Wang, Z.D. Wang, Q. Liu and P. Dyer, "Dissolved gas analysis of thermal faults in transformer liquids simulated using immersed heating method", IEEE Trans. Dielectr. Electr. Insul., 25(5): 1749-1757, 2018. (doi: 10.1109/TDEI.2018.007158)

[11] X. Zhang, Z.D. Wang and Q. Liu, "Interpretation of hot spot factor for transformers in OD cooling modes", IEEE Trans. Power Deliv., 33(3): 1071-1080, 2017. (doi: 10.1109/TPWRD.2017.2710087)

[12] W. Lu, Q. Liu and Z.D. Wang, "Pre-breakdown and breakdown mechanisms of an inhibited gas to liquid hydrocarbon transformer oil under negative lightning impulse voltage", IEEE Trans. Dielectr. Electr. Insul., 24(5): 2809-2818, 2017. (doi: 10.1109/TDEI.2017.006416)

[13] Y. Gao, B. Patel, Q. Liu, Z.D. Wang and G. Bryson, "Methodology to assess distribution transformer thermal capacity for uptake of low carbon technologies", IET Gener. Transm. Distrib., 11(7): 1645-1651, 2017. (doi: 10.1049/iet-gtd.2016.0722)

[14] X. Zhang, Z.D. Wang and Q. Liu, "Prediction of Pressure Drop and Flow Distribution in Disc-Type Transformer Windings in an OD Cooling Mode", IEEE Trans. Power Deliv., 32(4): 1655-1664, 2017. (doi: 10.1109/TPWRD.2016.2557490)

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transformer@manchester.ac.uk