FEATURE

TRANSFORMERS POWER THE WORLD

Power Transformer Research in Four Continents

Tapan Saha, Stefan Tenbohlen, Zhongdong Wang, Yang Xu, and Yuanxiang Zhou

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TRANSFORMER RESEARCH IS A SPE-cialized area of electrical engineering that requires a high level of investment in laboratory infrastructure. Many high-voltage (HV) and insulation research facilities have closed at numerous universities over the last three decades. However, due to the increasing proliferation of renewable energy sources, the need for power transformers has increased; concurrently, there has been a global shortage in the supply of new transformers. These issues therefore support the need for innovative research into power transformer design, particularly the use of transformer operation in a renewable-dominated power grid, as well as the use of sustainable materials for transformer construction, e.g., natural ester oil replacing mineral oil. The training of future engineers and the upskilling of the current workforce with specialist knowledge in transformer design and operation is becoming more important than ever. To this end, several global research-intensive universities have formed a virtual alliance, the University Transformer Research Alliance (UTRA),

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to share research and training expertise in power transformers. This article introduces power transformer research and training activities in eight universities across Asia, the Pacific, Europe, and North America.

Introduction: The UTRA

The UTRA was established in 2019 by leading transformer research groups in universities from Australia, China, Germany, and the United Kingdom. This virtual research alliance was established with the goal of developing a strategy to advance transformer research aligned with low-carbon energy requirements. The objective of this alliance is to work closely with the wider power transformer community, including manufacturers, power utilities, materials providers, and test/service businesses, to deliver fundamental and engineering research. It is also tasked with providing high-quality postgraduate education/training of students as well as upskilling of the current engineering workforce. Many universities and research institutions around the world are working on power transformer-related research; however, at the time, it was felt that there was no coordinated effort to build strong partnerships and share knowledge between these groups other than through organizations such as CIGRE and related IEEE activities. It was also observed that with the increasing number of researchers working in the field, there was increased duplication of work, which is due to a lack of communication between researchers and groups. To improve this situation and build better collaboration, five internationally leading transformer research groups established the UTRA, with the view of reaching out to transformer researchers worldwide and together advancing the state of the research at a faster pace with better alignment to low-carbon Energy requirements.

Currently, UTRA membership includes five full members: the University of Queensland (UQ) in Australia, Tsinghua University and Xi'an Jiao Tong University in China, the University of Stuttgart in Germany, and the University of Manchester in the United Kingdom. The alliance has recently accepted three associate members: the Université du Québec à Chicoutimi in Canada, Universiti Putra in Malaysia, and University of Exeter in the United Kingdom. This article will report on some major activities conducted by the alliance members as well as discuss future planning for a more coordinated effort in this important area. Alliance members meet at regular intervals as well as rotate the leadership team annually, publish joint research articles of interest, maintain an up-to-date website with relevant technical posts, update their publications and activity reports regularly, and organize an annual workshop to share knowledge and promote excellence in transformer research. Up to now, activities have been limited to alliance members; in the future, this will be extended to external entities consistent with the objectives of this alliance.

Transformer Research at the UQ in Australia

The UQ's transformer research is hosted within the Power, Energy, and Control Engineering Discipline in the School of Electrical Engineering and Computer Science (EECS). With a long history of transformer-related research of more than 35 years, the UQ established the Australasian Transformer Innovation Centre (TIC) in 2017 with a focus on asset management of power transformers in a modern electrical network. TIC comprises more than 20 members from electricity network operators (transmission and distribution utilities), transformer and other accessory manufacturers, consultants, multinational energy companies and specialist service providers, and several universities from Australia and abroad. TIC's purpose-built laboratory houses a 468-kVA 22/4.5/0.415-kV research-grade power transformer filled with ester oil and fitted with numerous online sensors donated by Wilson Transformer and Dynamic Ratings. TIC uses commercial-grade testing equipment to perform testing and research activities. These include time-domain spectroscopy and frequency-domain dielectric spectroscopy, frequency response analysis (FRA), partial discharge (PD) monitoring [IEC60270, high-frequency current transducer (HFCT), and ultrahigh-frequency

(UHF)], water activity measurement using capacitive and fiber-optic sensors, and heating and temperature monitoring by thermal infrared camera.

The center also has oil and paper accelerated aging test facilities. TIC researchers have developed numerous tools for use by industry. Recently, from a completed research project, researchers developed a software tool to assess the replacement priority of transformers in a fleet based on their operating conditions and failure statistics. In this tool, users can define weighting factors based on their own experience in their industry. TIC has also developed a PD identification tool using online measurements acquired via a high-frequency current transducer and making use of extensive signal processing tools, as outlined in Figure 1. The PD identification tool comprises four principal components: 1) PD signal denoising, which reduces noise contamination in the originally measured PD signals; 2) PD signal representation and feature selection, aimed at extracting a subset of informative yet nonredundant attributes from the raw PD data; 3) multisource PD signal separation, which partitions mixed PD measurements into distinct clusters, each corresponding to an individual PD source; and 4) PD source classification, which determines the specific type of PD responsible for the discharge occurring within the transformer.

Researchers at the UQ have a long history of successful commercialization of their generated intellectual property (IP), and extensive use of generated IP is made by several global industries. Over the last 10 years, UQ researchers have been involved in a small-to-medium enterprise startup, AURTRA. AURTRA was established in 2016 upon the foundation of 25 years of transformer research in hardware and software technology licensed from the UQ in the field of transformer monitoring and asset management, as shown in Figure 2. After five years of impressive performance and successful commercial usage of their developed technology by many utilities locally and internationally, AURTRA was acquired by French multinational Schneider Electric in a multimillion-dollar deal in 2021.

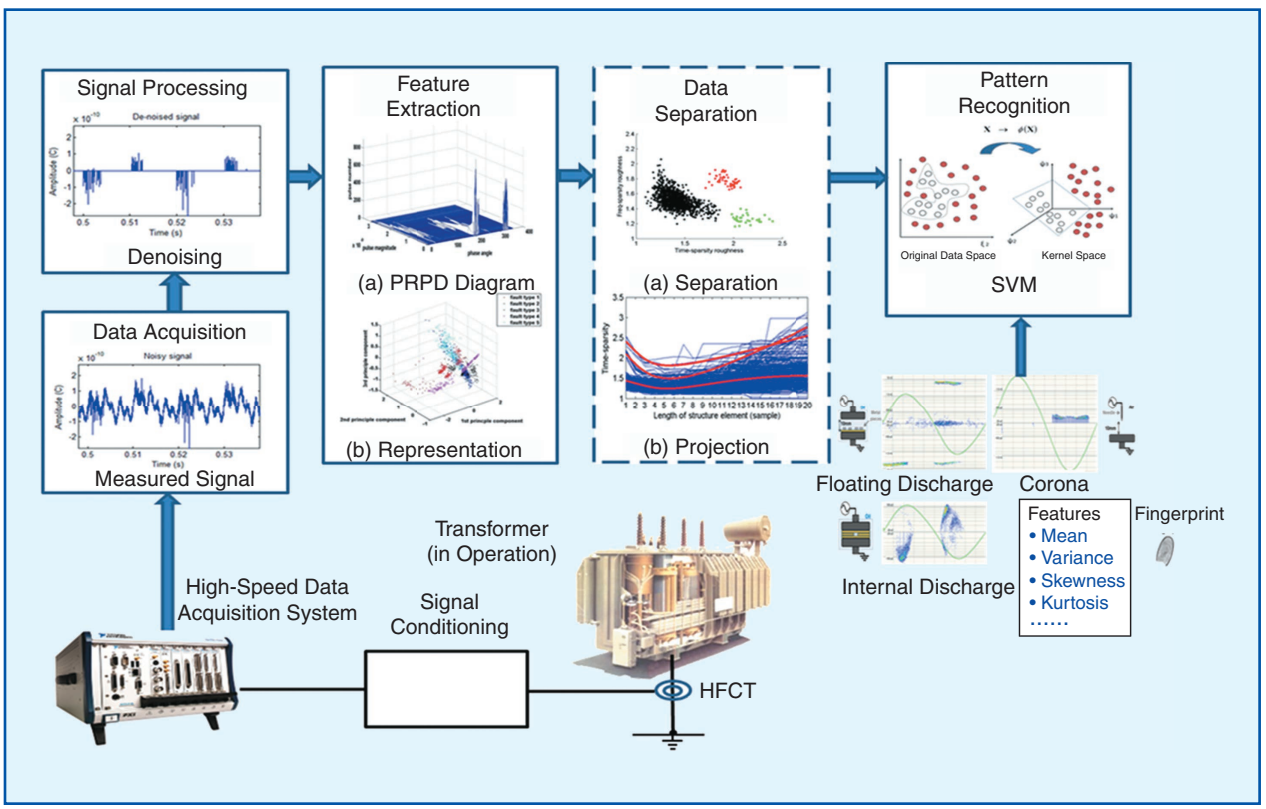

Figure 1. PD signal processing software tools developed at the UQ by TIC. SVM: support vector machine; HFCT: high-frequency current transducer; PRPD: phase-resolved partial discharge.

TIC offers continuing professional development (CPD) courses purpose-built for the future skill needs of the industry with content delivered by acclaimed transformer experts both locally and internationally. The CPD program brings a total focus on best practices in asset management for power transformers. Figure 3 shows attendees of a CPD course delivered by TIC at the UQ. Member organizations of TIC reap the benefits of this focus through reduced costs, increased asset performance and reliability, and keeping abreast with the latest asset management breakthroughs. The future research of TIC is focused on digital twin technology for power transformers, the application of artificial intelligence (AI) and machine learning to transformer remaining life estimation, and understanding the impact of renewables-associated harmonics and switching transients on transformer life. Additional information on TIC can be obtained from https://eecs.uq.edu.au/australasian-transformer-innovation-centre.

Figure 2. From left: the UQ's Prof. Tapan Saha and Aurtra CEO Terry Woodcroft.

Figure 3. A CPD course delivered by TIC at the UQ.

Transformer Research at Tsinghua University in China

Transformer research conducted at Tsinghua University, along with their collaborators such as China State Grid and Southern Power Grid, has contributed extensively to China's ultra-HV development. Transformer research facilities include an HV laboratory, a PD laboratory, a space charge laboratory, and an improved paper-making laboratory. Facilities at the HV laboratory include a 1,500-kV AC test set, a 1,400-kV DC test set, a 7,200-kV impulse generator, and a scale prototype of a converter transformer. In addition, other laboratories are equipped with various facilities related to PD measurement, space charge measurements, mechanical vibration measurements, vibro-acoustic measurements, temperature monitoring, transformer bushing sealing, dielectric measurements, and material preparation and processing systems. Figure 4 provides some examples of the research and development achievements of the team at Tsinghua University.

Transformer Research at Xi'an Jiao Tong University in China

The Transformer Research Group at Xi'an Jiao Tong University (XJTU) focuses on insulation material, transformer design, condition monitoring and assessment, on-site technology, and protection systems. Figure 5 shows the laboratory facilities at XJTU.

Beyond academic research, the transformer research group collaborates with transformer industry leaders such as the State Grid Corporation of China, China Southern Power Grid, China Three Gorges Renewables Co., China Electrical Equipment Group Co., TBEA, CHINT, Siemens, and Hitachi Energy. This collaboration explores new technology innovations and performs feasibility assessments in electrical equipment development and maintenance.

XJTU researchers are involved in many research projects, including high-energy arc discharge failures of extra-HV transformers, operations and maintenance technology for offshore wind power

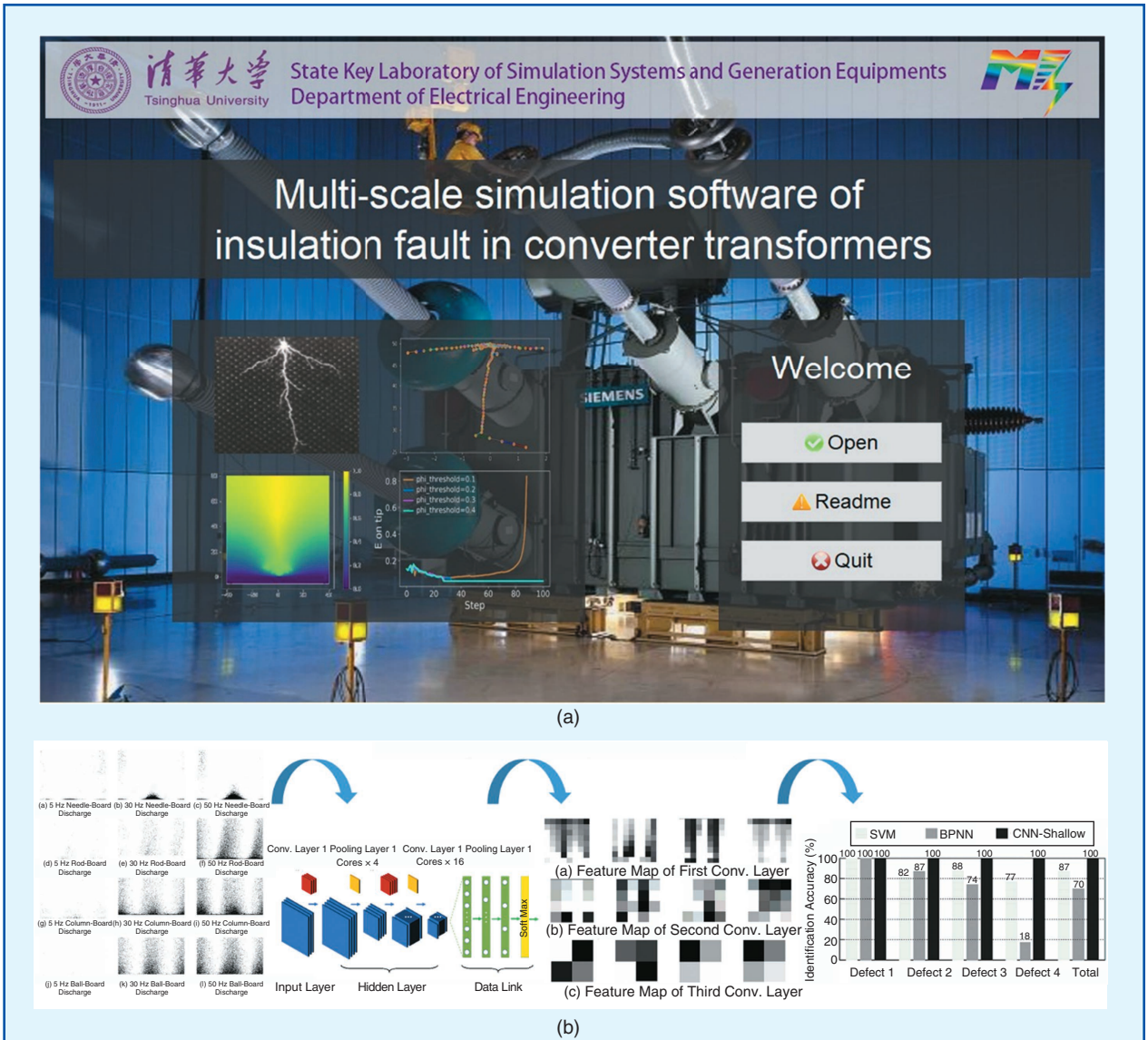

Figure 4. The condition monitoring tool developed at Tsinghua University. (a) Multiscale simulation software of insulation fault in converter transformer developed by Tsinghua University. (b) The pattern recognition method of PD in oil-paper insulation based on the multichannel convolutional (Conv.) neural network (CNN). BPNN: backpropagation neural network.

Figure 5. (a)–(c) The laboratory facilities at Xi'an Jiao Tong University.

The University of Stuttgart hosts the Institute of Power Transmission and High Voltage Technology (IEH), which is the center for transformer-related research.

converter transformers, 500-kV ester insulating liquid transformers, digital twin technology for power transformers, bushing of converter transformers, diagnosis of insulation deterioration in oil-immersed power transformers and accessories, evaluation of SF_6 gas transformers, and abnormal discharges in ultra-HV converter transformers.

XJTU offers a postgraduate program in cooperation with Siemens (China) and Tebian Electric Apparatus Stock Co. (TBEA). XJTU also delivers advanced technical training for engineers in the transformer industry. Researchers from XJTU are involved in IEC, CIGRE, and IEEE working groups and related standard activities. The future research focus of XJTU is on digital twin technology for power transformers, low-maintenance offshore windfarm transformer development, transformers for distributed power grids incorporating photovoltaics, and energy storage and electric vehicle charging as well as environmentally friendly insulation materials development and transformer life extension.

Transformer Research at the University of Stuttgart in Germany

The University of Stuttgart hosts the Institute of Power Transmission and High Voltage Technology (IEH), which is the center for transformer-related research. The institute's primary research focus is on reliability, cost-efficiency, and sustainability of electric power supply. This includes studies in HV insulation performance, condition assessment, and the planning and operation of future power grids, particularly in the context of the increasing use of renewable energy. A major focus of IEH's research is on the electromagnetic compatibility of both power and automotive systems.

IEH is dedicated to the advancement of measurement techniques tailored for high-amplitude impulse voltages and transient electromagnetic fields. A particular focus of this research is on the detection and measurement of PDs, including innovative methods for noise reduction, as well as innovative approaches such as acoustic PD measurement techniques and UHF PD measurement and localization methods.

Operating electric power networks beyond their initial design levels and longer than their estimated life span requires detailed monitoring to ensure a safe and reliable power supply in the future (lifecycle management). To achieve this, IEH researchers develop and improve diagnostic tools for various equipment, such as PD measurement, FRA, moisture determination, dissolved gas analysis (DGA), vibration measurement, and online monitoring, as shown in Figure 6. These tools help predict the overload capacity and remaining life of power transformers. IEH develops service and maintenance strategies for HV equipment (asset management).

Key research focus areas at the University of Stuttgart in the field of power transformer include the simulation and design optimization of thermal behavior using computational fluid dynamics, detection and localization of PDs by conventional and nonconventional methods, evaluation of online monitoring data to model the operational behavior of power transformers, dynamic loading of power transformers, use of natural esters (dielectric strength, aging, diagnosis, etc.), investigation of oil conductivity, influence of DC currents on operational behavior, detection of winding deformations by FRA, determination of moisture in oil/paper insulating systems, and investigation of fault gas generation. These research efforts aim to enhance the performance, longevity, and reliability of power transformers, contributing to the overall efficiency and sustainability of electric power systems.

Transformer Research at the University of Manchester in the United Kingdom

Work in HV research at the University of Manchester dates to 1958 with the establishment of

the Cockcroft Laboratory within the University of Manchester Institute of Science and Technology (UMIST) premises. Since then, the university's HV laboratory has been instrumental in addressing energy challenges and is equipped to manage testing for 400-kV power systems. In 2017, the laboratory was expanded with new equipment, including 800-kV AC and a 600-kV DC test sets, complementing the existing 2-MV impulse generator donated by the National Grid in the early 1980s. Additionally, the facility features multiple small-scale test cages and a dielectric materials laboratory equipped with state-of-the-art material processing and characterization equipment, including an air-circulating oven, a vacuum oven, a gas chromatography-mass spectrometry unit, a high-performance liquid chromatography (HPLC) unit, a Fourier transform infrared spectroscopy unit, a Karl Fischer titrator for moisture determination, an acidity titrator, and other dielectric measurement systems. In 2022, the lab was relocated to the Manchester Engineering Campus.

Manchester's transformer research team's work over the past two decades has significantly influenced the design and development of ester-filled power transformers. The Transformer Research Consortium, formed in 2005, serves as a collaborative platform for experts from various sectors to address industry-wide transformer challenges. Having completed four successful phases, the consortium

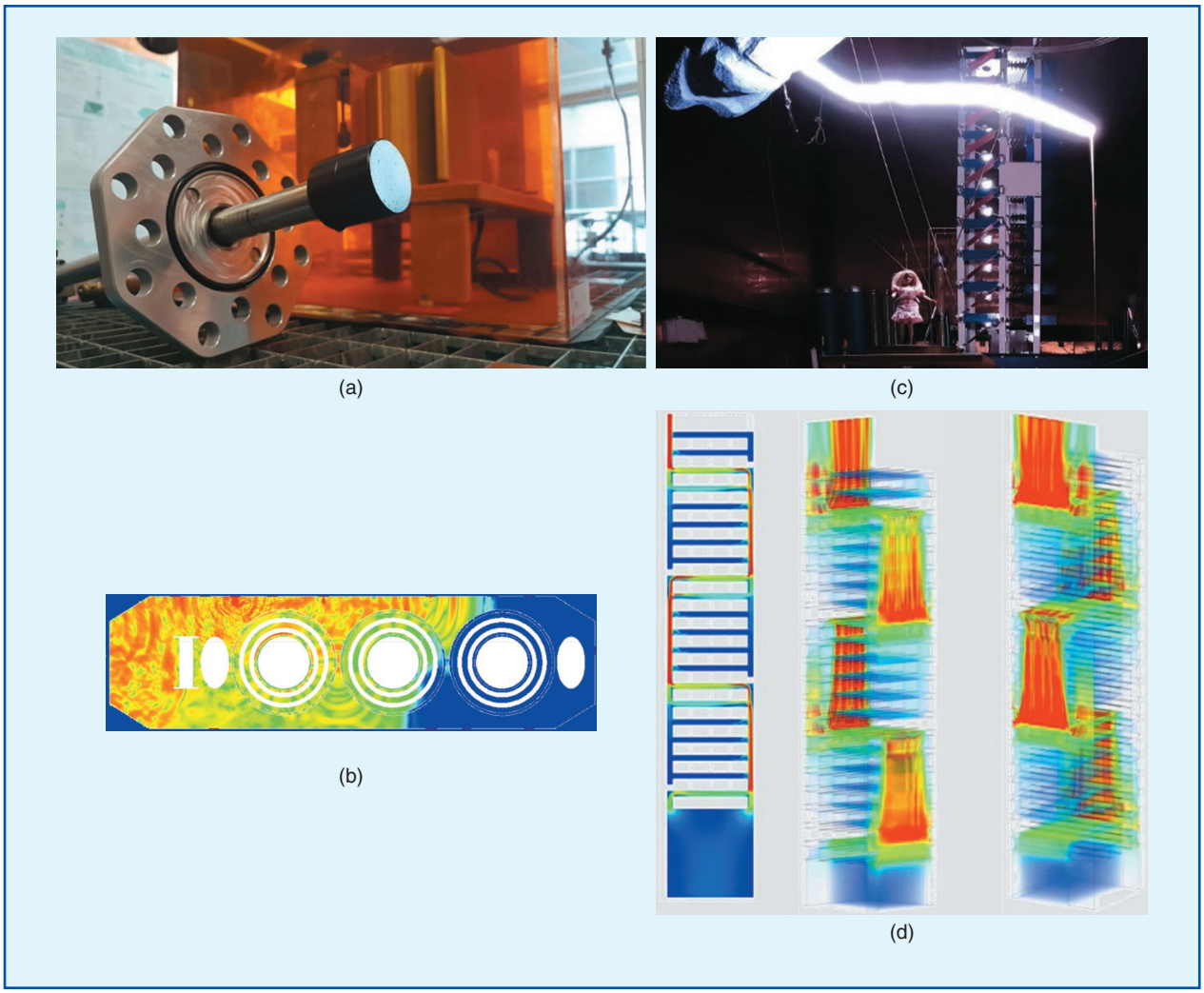

Figure 6. Innovative research activities with some outcomes at the University of Stuttgart. (a) UHF PD Sensor. (b) Electromagnetic wave propagation inside the transformer tank. (c) Lightning protection. (d) Oil velocity within an oil-directed-cooled winding.

is now in its fifth phase, focusing on areas such as condition assessment, asset management, thermal modeling, and discharge and breakdown mechanisms. Laboratory facilities at the University of Manchester are shown in Figure 7. The University of Manchester has completed projects for the design and deployment of high-performance power transformers immersed in biodegradable fluids (BIOTRAFO), unlocking power transfer capability through quadrature boosters, power electronics-enabled transformers for battery energy storage systems, Transformer Research Consortium Phase 4, and heat recovery on grid transformers.

Some of the ongoing projects related to transformers include transformer end-of-life analysis, digital tools in designing DC isolation transformers, Transformer Research Consortium Phase 5—aging assessment of transformer insulation, thermal modeling, lifecycle analysis, digital twin for transformers, development of knowledge and technology to implement retro filling in power transformers using biodegradable or recycled fluids, and fostering circular economy and voltage interaction and thermal dynamics of transformer tertiary connection.

University of Manchester researchers are involved in numerous CIGRE, IEEE, and IEC working groups. The university's future research directions include projects in digital twins for power transformers, combined chemical and physical mechanisms-based condition monitoring data interpretation, multiphysics modeling for transformer design and asset management, and aging mechanisms studies through modeling and realistic dual temperature aging systems. Future research involves pre-breakdown and breakdown mechanisms of dielectrics for DC applications, including converter transformers and battery energy storage systems, and physics-inspired AI and machine learning for transformer condition assessment.

Transformer Research at the University of Quebec at Chicoutimi in Canada

The University of Quebec at Chicoutimi (UQAC) in Canada focuses on teaching and research activities in the field of electrical energy and HV engineering. Research at UQAC focuses on the aging of oil-filled equipment installed on HV systems. The primary objective of the work is to deepen the understanding of the processes leading to the degradation/aging of insulation within liquid-filled power equipment. Simultaneously, it aims to provide engineers and designers with innovative materials and practical tools for analysis and design. The team's current research interests include insulation material and design, condition monitoring and assessment, on-site technology, and digital twining in the transformer area. Further topics of research include lightning, arc physics and related phenomena, outdoor insulation, general HV engineering, and numerical simulations.

The facilities at UQAC include a 350-kV AC test set, a 300-kV DC test set, a 5-kA current source, and 200-kV and 800-kV impulse test sets. Facilities also include various material test and analysis equipment, such as a Novocontrol broadband dielectric measurement system, a DIRANA dielectric FRA system, an IDA200 dielectric spectroscopy analyzer, Fourier transform infrared spectroscopy, DGAs, frequency response analyses

Figure 7. Laboratory facilities at the University of Manchester. (a) The HV Laboratory at the UoM. (b) The specialist laboratory at the UoM. (c) Breakdown in the ester liquid.

(FRAs), return voltage measurement, and HPLC. These and other equipment and facilities, such as mechanical convection ovens, climate chambers, and vibration/acoustic tests, are shown in Figure 8.

Hydro Québec, Hitachi-Energy, Rio Tinto, Rugged Monitoring, Hexacode Solutions, EDF-France, and RTE-France are partners of research projects at UQAC. Some of the projects include the development of knowledge and models applicable to the concept of digital twins for power transformers, aging, diagnostics and monitoring of power transformers, biodegradable oils as an alternative to mineral oils in distribution and power transformers, and geomagnetic disturbance in modern societies and technological infrastructures. UQAC members contribute to innovative works conducted by the CIGRE, IEC, IEEE, and ASTM organizations.

Transformer Research at the University Putra Malaysia

The transformer research team at the University Putra Malaysia (UPM) is part of the Advanced Lightning, Power, and Energy Research (ALPER) Centre. The transformer research facilities at UPM comprise an HV and a dielectric laboratory. Numerous instruments are available for sample preparation and electrical testing. The dielectric laboratory is equipped with a vacuum and air-circulating oven, an AC breakdown test set, and an oil processing system. The HV laboratory is equipped with a 420-kV impulse test set, a 100-kV AC test set, a 130-kV DC test set, a high-speed imaging camera, and a PD detector, as shown in Figure 9.

UPM collaborates with industrial partners, such as Hyrax Oil Sdn Bhd, TNB Labs Sdn Bhd, MTM Transformer Manufacturing Sdn Bha, and Xair Energy Sdn Bhd. UPM researchers are involved with research projects in the development of alternative insulation liquids and solid insulation for transformers, aging assessment of insulation and asset management of transformers, thermal and mechanical modeling of transformers, condition monitoring of transformers based on advanced

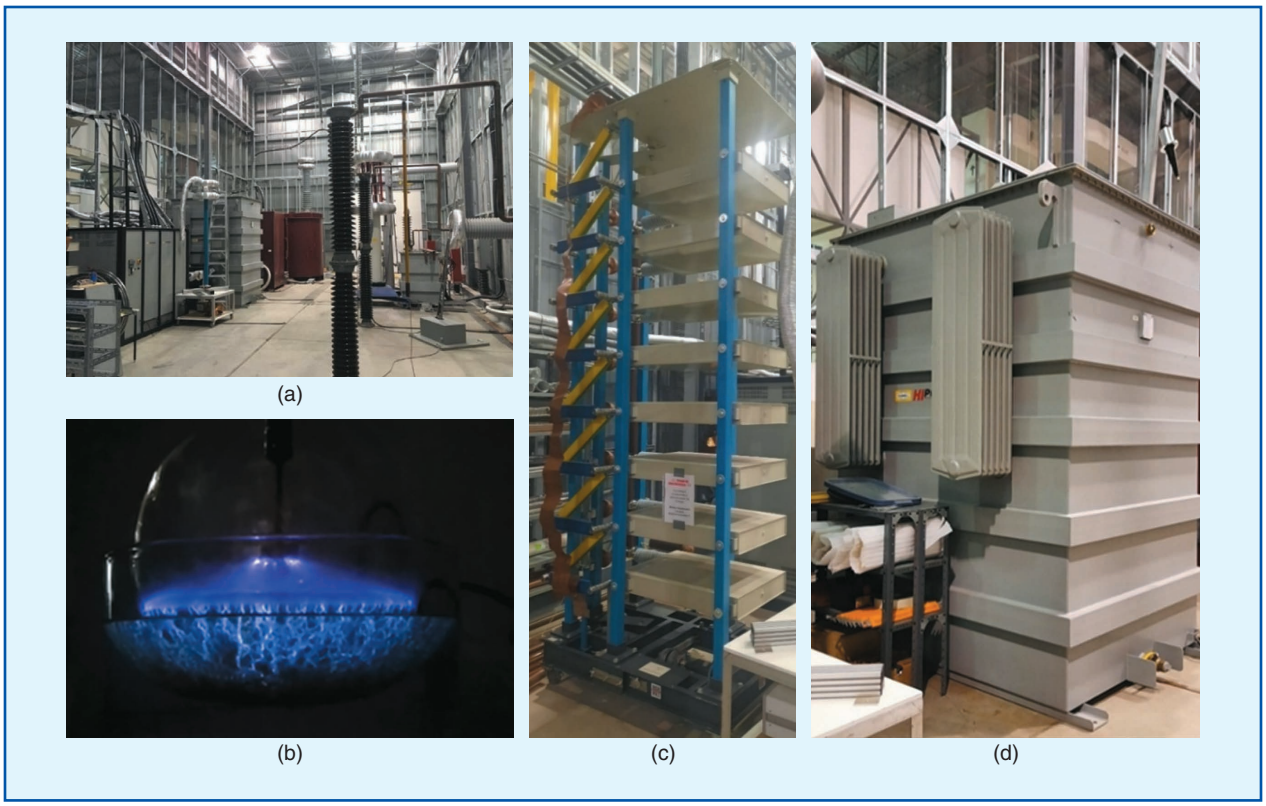

Figure 8. Laboratory facilities at UQAC. (a) An overview of the HV laboratory. (b) The stability of oil under electrical discharge. (c) An 800-kV impulse voltage (d) A 300-kV DC test transformer.

electrical analyses, and the application of nanomaterials in liquid insulation.

UPM researchers contribute to CIGRE, IEC, and IEEE committees and include working groups on HV test techniques from the Department of Standards in Malaysia. UPM's future research directions include the application of nanomaterials in insulation paper and pressboard and the development of monitoring devices for the condition monitoring of insulation in transformers.

Figure 9. The laboratory facilities at the Universiti Putra Malaysia.

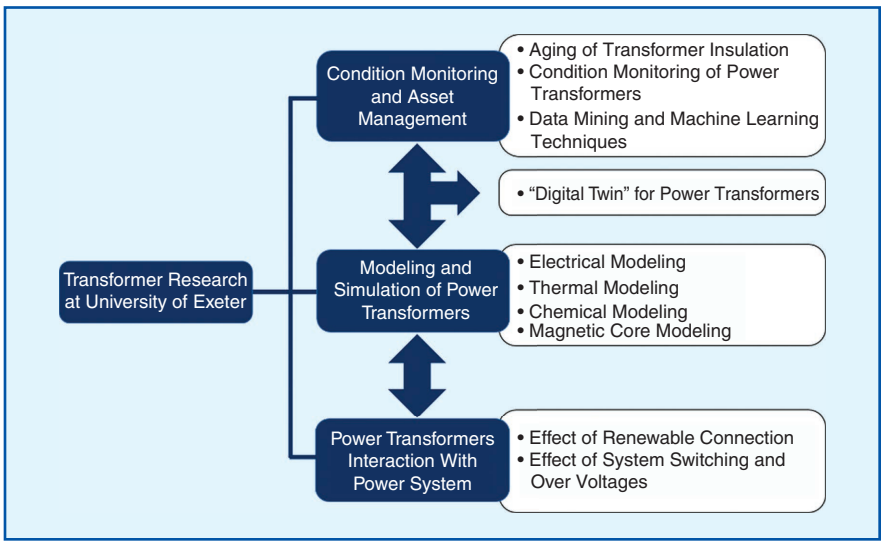

Figure 10. The research focus of the University of Exeter transformer research team.

Transformer Research at the Centre for Smart Grid in the University of Exeter in the United Kingdom

The University of Exeter transformer research team hosts a dielectric materials laboratory, which has facilities to preprocess and characterize dielectric materials. The main equipment in the laboratory includes a Karl Fischer titrator for moisture measurement, a potentiometric titrator for acidity measurement, an online dissolved gas analyzer, HPLC, HV AC and DC sources, PD detectors, an AC breakdown tester, and vacuum and air-circulating ovens.

The University of Exeter has industry collaborations with the National Grid, UK distribution network operators, and other national and international industries. Researchers participate in projects including unlocking power transfer capability through a quadrature booster, the application of special transformers in LV networks to mitigate voltage unbalance, and power electronics-enabled transformers for battery energy storage systems. The research focus of the university transformer research group is shown in Figure 10. The research laboratory facilities of Exter University are shown in Figure 11.

The University of Exeter offers an M.Sc. program in electrical power and smart grids, with researchers contributing to CIGRE activities in the United Kingdom. Future research directions include digital twinning and online monitoring of power transformers and the application of special transformers in transmission and distribution networks to mitigate network challenges under future energy scenarios.

Conclusion

UTRA members regularly organize meetings to discuss research and educational challenges, along with opportunities that may arise for work in transformer operation and

Figure 11. The University of Exeter transformer research facilities.

maintenance. Each country has its own strengths in industry-academia collaborations, along with strategic research objectives geared toward maintaining that country's transformer fleet's reliable operations in the context of renewables-dominated power systems. Research in power transformers needs costly laboratory facilities along with strong industry/government funding support for maintaining these facilities. UTRA members are working on traditional condition monitoring techniques, biodegradable insulating oils, and the application of AI and machine learning tools for the development of advanced tools for life assessment and online monitoring of transformers. UTRA members regularly commercialize their IP through startups and multinational companies. Members are jointly publishing in important topic areas of interest in transformer research and education. Further, UTRA members regularly organize annual conferences for member universities' researchers and regularly participate in CIGRE and IEEE/IEC working groups and study committees. UTRA has the potential to expand its membership to major industrial research organizations and universities in other countries to foster stronger coordinated collaborations.

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Further reading

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Biographies

Tapan Saha is with the University of Queenlsland, Brisbane, QLD 4072, Australia.

Stefan Tenbohlen is with the University of Stuttgart, 70174 Stuttgart, Germany.

Zhongdong Wang is with the University of Manchester, M13 9PL Manchester, U.K.

Yang Xu is with Xi'an Jiao Tong University, Xi'an 710049, China.

Yuanxiang Zhou is with Tsinghua University, Beijing 100084, China.