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SPECIAL REPORT FOR SC A2 POWER TRANSFORMERS AND REACTORS

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PS3
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SCOPE OF STUDY COMMITTEE A2

The technical field of activity of Study Committee A2 is:

- Power transformers, including industrial, DC converter, generator step-up and phase-shifting transformers for distribution, transmission, and renewable energy applications,
- Reactors, including shunt, series, saturated, and smoothing,
- Transformer components including bushings, tap changers and accessories.

Within its technical field of activity, Study Committee A2 addresses topics throughout the asset management life-cycle phases; from conception; through research, design, production, deployment, operation, and end-of-life. At all stages, technical, safety, economic, environmental, and social aspects are addressed as well as interactions with, and integration into, the evolving power system and the environment. All aspects of performance, specification, testing, and the application of testing techniques are within scope, with a specific focus on the impact of changing interactions and demands due to evolution of the power system. Life cycle assessment techniques, risk management techniques, education and training are also important aspects.

Within this framework additional specific areas of attention include:

- Theory principles and concepts, functionality, technology development, design, performance and application of materials, efficiency,
- Manufacturing, quality assurance, application guidance, planning, routing and location, construction, installation, erection, installation,
- Reliability, availability, dependability, maintainability and maintenance, service, condition monitoring, diagnostics, restoration, repair, loading, upgrading, uprating,
- Refurbishment, re-use/re-deployment, deterioration, dismantling, disposal.

The Preferential Subjects (PS) for the 2026 Study Committee A2 Group Discussion Meeting are:

PS1: Major Challenges to the transformer industry
PS2: The Transformer digitalisation journey
PS3: Failure prevention, detection and investigation

PARTICIPATING IN THE 2026 PARIS SESSION

You are invited to participate in discussing this Special Report at the SC A2 session held on **Tuesday August 25th, 2026 from 08:45 to 18:00 at l'Amphithéatre Bleu** in the Palais des Congrès de Paris.

The reporters have prepared a list of questions, these are not specifically aimed at the papers' authors, but are synthesised from common issues and trends identified in across the papers. This provides the opportunity for a broader response and participation in the discussion session. We encourage you to share your views or experiences in response to the specific questions in this report. During the Group Discussion Meeting, each prepared contribution will be allocated a time slot of three to four minutes for a presentation.

Procedure for contributions:

1. Contributors should upload contributions on the registrations portal – "Contributions to Group Discussion Meetings" section - using your existing account and own credentials **before 7th August 2024**, for a prior screening and a good organization of the Group Discussion Meeting. Important points:
2. Access to contribution uploading is given only to duly registered delegates.
   - Registration to CIGRE Session needs to be completed before uploading contribution(s) online.
   - Contributions uploading will be open at start of June.
3. Special Reporters will review the prepared contributions (Power point presentation with max **4** slides including the title slide, and a written word file with max 1000 words). A guide for contributors as well as templates and sample pages will be available on the Paris Session webpage. Important notice: No commercial names are to be included in the presentation or the written summary (even TSO/DSO names).
4. Any recommendations or changes to the contributions will be provided to the contributors by the Special reporters directly on the Registration platform between 7th of August and 14th of August 2026. Contributors are encouraged to visit their account on the registrations portal to see the result of this review.
5. All contributors with accepted/finalised contributions will be contacted by the Special reporters between 7th of August and 14th of August 2026, to finalize the presentation and receive the instructions regarding the session.
6. Important note:
   - All contributions must be uploaded prior to the Conference in Paris.
   - Last minute changes to the contributions will not be granted.
7. During the GDM the Study Committee Chair may call for spontaneous contributions, which will only be verbal with no slides. All attendees are eligible to make such a contribution. Attendees who provide a spontaneous contribution are allowed to deliver a written contribution which will be included in the Session Proceedings. This text is required to be forwarded within a maximum delay of two weeks after the Study Committee GDM Session (i.e. by date) to the SC Secretary (email address).
8. It is expected that the questions relevant to the Preferential Subjects will attract many prepared contributions. The number of contributions for each Preferential Subject (PS1, PS2 and PS3) may need to be limited. The selection will be based on relevance, quality and time of submission of the contribution.
9. Please note that accepted contributors may be required to attend a short pre-session meeting with the Special Reporters, SC Chair and SC Secretary on **Monday August 24th, from 9h00 to 12h00 in room 234** at the Palais des Congrès to finalise presentation arrangements. The purpose of this short meeting is to review the final details of their contribution and to receive the latest instructions (such as schedule).

POSTER SESSION

Authors of SC A2 Session papers are required to present their papers during the SC A2 Poster Session scheduled on **Monday August 24th from 14h00 to 18h00** in Halle Ternes on level 1. Template and instructions on poster preparation are available on the CIGRE 2026 Session website. Posters will be displayed on digital screens. Poster presentations may be uploaded on the ConfTool platform from May 18th until June 29th at the latest for review by the poster session conveners. Poster conveners may ask for changes, final version must be uploaded by August 14th. It should be noted that authors will **not** have the possibility to upload their own file on the day of the Poster Session. If the author(s) cannot attend the Poster Session he/she or the relevant National Committee is requested to send a substitute.

PS1: MAJOR CHALLENGES TO THE TRANSFORMER INDUSTRY

The subject covers:

- Advances in transformer engineering, including the application of novel materials, advanced insulation systems, and multi-physics modeling to overcome core design limitations. Mitigation of critical dielectric and thermal stresses, resulting in quantifiable improvements in operational efficiency, component reliability, and the accuracy of asset performance characterization.
- Management of aging infrastructure amidst volatile global supply chains. Data-driven methodologies for risk assessment, life extension, and strategic procurement for optimizing capital investment and ensuring long-term grid reliability.
- Environmental performance and climate resilience of power transformers. Methods to quantify and reduce environmental impact through life-cycle assessments, sustainable insulating liquids, recycled materials, and decarbonisation of the manufacturing process. Strategies to improve asset resilience against the physical threats posed by climate change.

A total of 38 papers were submitted on this preferential subject, of which 21 were selected for the Special Report. These 21 were further categorized into the following subtopics;

- PS1-1: Transformer Design, Technology Innovation & Performance Improvement (8 papers).
- PS1-2: Asset Management, Reliability, Operations & Supply Chain Strategy (5 papers).
- PS1-3: Sustainability, Environmental Impact, & Climate Resilience (8 papers).

PS1-1: Transformer Design, Technology Innovation & Performance Improvement

Paper 10279 (Netherlands, Sweeden, Italy) details a test project to uprate a spare 50/10kV 24/30MVA ONAN/ONAF power transformer by replacing its mineral oil with a high-performance, low-viscosity, bio-based insulating fluid and adding additional fan capacity. The results from extended heat-run tests showed significant reduction in hot-spot temperatures, with increased oil flow through windings and radiators observed along with more effective heat dissipation with the additional fans, improving the tested transformer's rating to approximately 125% of its original rating.

Paper 10658 (Brazil, Germany) compares modelling approaches to evaluate dielectric withstand for shunt reactors due to disconnect switching transients, specifically evaluating 550kV, 164.7 MVAR shunt reactor design. Findings indicated that while black-box models yielded similar results, accurate surge arrester representation and thorough analysis of manufacturer's time domain response in the high frequency range were important to accurate results.

Paper 10661 (Brazil, Germany) presents a comparative investigation of the transient response of continuous disc and interleaved disc winding configurations using an analytical white-box model, with results validated in laboratory tests. The white-box model was chosen as it provides a high level of detail, explicitly representing winding geometry, material properties, and electromagnetic interactions. The results demonstrated that winding geometry has a direct influence on internal transient voltage distribution, concluding that the integration of detailed analytical modelling with experimental validation is fundamental to accurately capturing the effects of high-frequency transients.

Paper 10761 (Japan) shares findings on the thermal ageing behaviour of thermally upgraded paper in a mineral oil-designed transformer retrofilled with natural ester. Combining the TC model and experimentally obtained deterioration characteristics of thermally upgraded paper, identical annual load and ambient temperature profiles were used to calculate the winding temperature history and lifetime of the thermally upgraded paper for both mineral oil and natural ester operation. Results showed that while natural ester increased the hot spot winding temperature, it markedly slowed thermally upgraded paper deterioration.

Paper 11052 (Italy) discusses an effort to improve results of legacy models to predict transformer load losses using finite element method (FEM) simulations and machine learning. Using a dataset of approximately 350 unique power transformer designs, detailed 3D FEM simulations were used to train the tool and test multiple machine learning techniques. 2D FEM simulations together with machine learning algorithms were used to predict power transformer load losses, and findings showed that Linear Regression models performed better than more complex machine learning techniques, although future work will continue to evaluate machine learning models as larger datasets become available.

Paper 11659 (Türkiye) details findings on the calculation of winding eddy losses, comparing IEC 61387-1:2011 standard calculations to calculations performed with the finite element method (FEM). Using both the IEC standard calculations and FEM models, the effect of harmonic spectrum on winding eddy losses was analysed, showing a dramatic increase in harmonic eddy losses which highlights the need for relevant calculations to be made on transformers loaded with harmonic currents. The FEM method was difficult to analyse and model, and the authors concluded that IEC 61837 Annex A.2 appears to be a more practical approach.

Paper 11825 (Norway, Austria, Sweeden, Slovenia) studied the cold-start thermal response of oil-immersed power transformers at low ambient temperatures ranging from -40°C to 20°C. When a cold start is carried out in arctic environment, the winding's hotspot thermal response typically exhibits a temporary temperature overshoot before reaching steady state, which can lead to deterioration of the transformer's insulating system. The contribution experimentally studied these impacts from the time of the cold start through temperature steady state at thermal equilibrium, highlighting operational challenges faced by transformers in arctic environments.

Paper 12374 (Czech Republic, Germany, USA, Ireland) discusses advanced dry-type transformer design solutions, including transient voltage resilience, enclosure design for thermal management and skid-platform installation optimized through CFD and FEM simulations, and efficient dedicated low-voltage busway interface for hyperscale AI-datacentre applications.

The papers submitted under PS1-1 highlight the increasing use of advanced materials, enhanced cooling methods, and detailed modelling techniques to improve transformer performance, flexibility, and resilience under evolving operating conditions. Several contributions (10279, 10761) demonstrate that retrofilling transformers with alternative insulating fluids and increasing cooling capability can significantly improve loading capability and thermal performance. While increased loading capability may provide valuable flexibility for utilities facing rapidly growing demand, there remains an important discussion regarding how long-term insulation ageing, operational uncertainty, and cumulative thermal stresses should be assessed when extending the capability of existing assets beyond their original design intent.

Another key theme is the growing reliance on advanced modelling techniques to better understand transformer behaviour under increasingly complex electrical stresses. Papers 10658 and 10661 both emphasize the importance of detailed high-frequency transient modelling for accurate prediction of dielectric stresses within transformers and shunt reactors. In parallel, Papers 11052 and 11659 investigate the application of FEM simulations and machine learning methods to improve the prediction of load losses and harmonic eddy losses. The papers show that while advanced numerical methods can improve design accuracy and asset performance assessment, model validation through testing and practical implementation remains essential, particularly for high-frequency transient phenomena and harmonic-rich operating environments.

The contributions also reflect the broader shift toward transformers operating in more demanding and specialized applications. Arctic cold-start conditions, renewable integration, harmonic loading, and hyperscale AI datacentre applications introduce operating stresses that differ significantly from conventional service conditions. These evolving applications raise important questions regarding whether future transformer standards and design practices should increasingly account for extreme operating scenarios as part of baseline design requirements, or whether these edge-case conditions should primarily be managed operationally through monitoring, operational controls, and asset management strategies.

Q1.01: To what extent should OEMs, utilities, and standards organizations share responsibility for validating transformer uprating strategies and defining acceptable operational limits for retrofilled or modified transformers? Where should utilities draw the line between "safe capacity gain" and "hidden life consumption"?
Q1.02: How can advanced modelling approaches, including FEM simulations, analytical white-box models, and machine learning techniques, be effectively validated to ensure reliable prediction of dielectric, thermal, and harmonic-related stresses?
Q1.03: Should future transformer design standards increasingly incorporate extreme operating scenarios, such as arctic cold-start conditions, high harmonic loading, and hyperscale datacentre applications, as baseline design requirements? Or is it more rational to design for typical conditions and manage edge cases operationally?
Q1.04: What are the most effective strategies for balancing highly specialized transformer designs for emerging applications with the need for practical manufacturability, operational flexibility, and economic feasibility?

PS1-2: Asset Management, Reliability, Operations & Supply Chain Strategy

Paper 10750 (USA) highlights the development of the Loss of Oil Lockout (LOL) scheme to address asset-level protection for rapid oil-loss events caused by physical damage, a concept which is not covered by existing substation security standards. The paper introduced a logic sequence capable of introducing mechanical indicators, consisting of the conservator tank liquid gauge, Buchholz relay, and main tank level gauge, in a progressive pattern that would act when all conditions signalled a true risk. The implementation of the LOL scheme highlights how asset-level automation can enhance grid resiliency against evolving physical threats.

Paper 10758 (Japan, Spain, Germany) details site assembly transformer technology developed to address logistical challenges where road and bridge limitations make transformer transportation and delivery difficult. The paper introduces the central innovation of the yoke-split structure, which optimizes the design of transformer configurations, streamlines logistics and installation, and enables applications for up to the 500kV class. The yoke-split designs were validated through a full-scale pilot project of a 525kV, 250MVA single-phase transformer.

Paper 11422 (Switzerland, USA, Germany) presents the development and deployment of a 58/65/93MVA reconfigurable area station transformer (AST). The AST Type 2 transformer supports multi-voltage and multi-impedance operation, managed by four deenergized tap changers and one on-load tap changer, and incorporates a compact design with "plug-and-play" features to simplify installation and transport, allowing for rapid response to mitigate unexpected outages. The paper shares details on the design, testing, and trial installation of the AST.

Paper 11723 (Spain) discusses a methodology of standardized transformer procurement which decouples technical validation from purchasing via a pre-approved Technical Data Sheet (TDS) for standard transformer families. The paper shares three cases with separate procurement constraints and challenges and quantified the effects of standardized procurement in per-unit terms, focusing on the impacts of decoupling technical validation, portfolio-level slot management, and multi-sourcing on a single TDS.

Paper 11955 (Germany, United Kingdom) shares maintenance guidelines for power transformers and shunt reactors used in AC and HVDC offshore substations, categorized by routine, planned, and unplanned maintenance. Typical maintenance intervals, durations, personnel requirements, and detailed descriptions of maintenance activities are shared for each class of maintenance, as well as responsibilities and interfaces between operator, platform designer, and OEM.

The papers submitted under PS1-2 reflect the growing challenges utilities face in maintaining grid reliability amid aging transformer fleets, constrained manufacturing capacity, extended lead times, and increasingly complex logistical and operational requirements. Several contributions focus on improving resiliency through enhanced operational preparedness, including rapid-response spare transformers, modular and site-assembled transformer solutions, and asset-level protection schemes intended to reduce the consequences of high-impact failure events.

A recurring theme throughout the papers is the increasing importance of flexibility and standardization in transformer fleet strategy. The development of reconfigurable spare transformers and site assembly transformer concepts demonstrates how utilities and manufacturers are adapting to transportation constraints, limited spare availability, and the need to reduce outage duration following unexpected failures. At the same time, standardized procurement methodologies and pre-approved technical specifications are being used to streamline purchasing processes, improve sourcing flexibility, and better manage limited manufacturing capacity across multiple suppliers.

The papers also highlight the growing need for closer coordination between asset management, procurement strategy, maintenance planning, and operational risk assessment. Contributions addressing offshore maintenance planning and asset-level automation illustrate how maintenance execution, monitoring, logistics, and system restoration planning are becoming increasingly interconnected. As utilities continue to face supply chain uncertainty and long replacement timelines for critical equipment, transformer strategy is evolving from a purely technical design exercise toward a broader lifecycle and resiliency-focused asset management approach.

<u>Q1.05:</u> What are the most effective approaches for balancing standardization, operational flexibility, and long-term reliability in transformer fleet management? With standardized designs and bulk procurement framework reducing lead times and costs, are utilities trading away too much long-term flexibility for short-term supply chain relief?
<u>Q1.06:</u> What level of flexibility should be incorporated into future spare transformer programs (multi-voltage, multi-impedance, modular assembly, transportability), and how should the associated cost and complexity be justified?

PS1-3: Sustainability, Environmental Impact, & Climate Resilience

Paper 10146 (France) shares results of a pilot project to reuse of secondary copper from a decommissioned transformer into a new transformer. The paper reviews the life cycle assessment (LCA) of two power transformers from cradle-to-grave and highlights the impacts of copper production on LCA. A simulated LCA using recycled copper was generated to highlight the benefits compared to traditional transformer manufacturing. The paper also discusses the full process to dismantle and recycle copper from an existing transformer.

Paper 10205 (India) reports on a comprehensive, field-validated cradle-to-grave life cycle assessment (LCA) and carbon footprint assessment of a 400kV, 500MVA transformer, allocated across manufacturing, transport, onsite commissioning, operation and maintenance, and end-of-life. The paper also identifies lifecycle “hotspots” and evaluate interventions via operations, manufacturing, and design to provide data for transformer fleet decarbonization planning.

Paper 10645 (Brazil, Spain) details a case study where a carbon footprint analysis and life cycle assessment (LCA) were used to evaluate between replacement and life-extension measures for two generator step-up transformers. The paper highlights a cradle-to-use LCA, encompassing raw material extraction, manufacturing, transportation, and operation, and excludes end-of-life disposal. The results showed that while new transformers demonstrate superior efficiency and emissions performance, life extension provided significant benefits in terms of cost, material reuse, and adaptability.

Paper 10760 (Japan) presents on the development of a 66kV, 20MVA gas-insulated transformer using nitrogen (N_2), developed with the aim of reducing the environmental impact of conventional SF_6 gas-insulated transformers. The paper reports on design challenges including unit size due to inferior cooling and insulation performance, and shares information and results on performance verification tests on this prototype natural origin gas-insulated transformer.

Paper 11015 (Brazil, China) discusses results from a case study assessing a novel 550kV, single-tower dry-type air-core shunt reactor, using life cycle cost (LCC) framework to provide a total cost of ownership (TCO) evaluation aimed to support utility investment decisions for all high-voltage shunt reactors in operation in Brazil. The study compares the 550kV dry-type shunt reactor with conventional oil-immersed alternatives, comparing inputs including footprint, operations & maintenance, transportation and assembly, and asset availably, ultimately reporting that single-tower dry-type air-core shunt reactors were a cost effective and risk-resilient alternative for high voltage power compensation.

Paper 12240 (Switzerland, France, Germany) shares a methodology of calculating the carbon footprint of power transformer manufacturing through life cycle analysis (LCA). It outlines key manufacturing steps and distinguishes between on-site and off-site processes and standardizes waste classification and quantification by calculating the carbon footprint per kilogram of nameplate weight (kgCO2eq/kg) for consistency and accuracy across transformer types. The findings identify electricity, gas consumption, steel manufacturing and hazardous waste as major contributors to the overall carbon footprint, and highlight the need for rolling, year-over-year data for accurate assessments.

Paper 12241 (Switzerland, Türkiye) explores the impact of climate change on transformer performance and longevity, focusing on the effects of rising ambient temperatures and increased electricity demand. The study utilized three-dimensional computational fluid dynamics to analyse temperature rise and hotspot formation under various conditions based on projected increase to temperatures, heat events, and electric demand, and presents a methodology for calculating the remaining transformer lifetime under different climate scenarios and load profiles. The paper concludes with proposed asset management strategies for transformer specification and design that consider these impacts.

Paper 12418 (Germany, Spain) highlights the design of a novel 250MVA, 765kV single-phase ester-filled autotransformer, discussing design challenges such as resilient dielectric design and UHV AC induced voltages of 970kV, a milestone in the application of ester technology at ultra-high voltages. The paper shares insight on the design, manufacturing, and testing of this unit, which is the world’s first ester transformer for this voltage class.

The papers submitted under PS1-3 highlight the increasing importance of integrating sustainability, environmental impact, and climate resilience into transformer design, manufacturing, and asset management strategies. Several contributions focus on the use of life cycle assessment (LCA) methodologies to quantify environmental impacts across transformer manufacturing, operation, refurbishment, and end-of-life processes. The papers demonstrate that material production, particularly copper and steel manufacturing, along with operational losses, remain major contributors to transformer carbon footprint. At the same time, the studies show that refurbishment, material reuse, and life-extension strategies can provide meaningful reductions in environmental impact while also helping utilities address supply chain constraints and extended equipment lead times.

A recurring theme throughout the papers is the need to balance sustainability objectives with long-term reliability, operational flexibility, and economic considerations. Contributions comparing refurbishment against replacement strategies demonstrate that while new transformers may provide improved efficiency and lower operational emissions, life extension and reuse strategies may offer advantages related to material conservation, cost, delivery schedules, and asset availability. Other papers investigate emerging technologies including recycled copper, ester-filled ultra-high voltage transformers, SF_6-free gas-insulated transformers, and dry-type air-core reactor solutions, illustrating the broad range of approaches being explored to reduce environmental impact while maintaining acceptable technical performance.

The papers also emphasize the growing influence of climate change on transformer specification and operation. Increasing ambient temperatures, changing load profiles, and more frequent extreme weather conditions are expected to affect transformer ageing, thermal performance, and asset lifetime. These contributions highlight the need for utilities and manufacturers to evaluate how future climate conditions, sustainability targets, and resiliency requirements should be incorporated into transformer procurement, design standards, and long-term asset management strategies.

Q1.07: Should utility fleet planning decisions, transformer loading guides and thermal design margins be revised to account for projected increases in ambient temperatures and more frequent extreme weather events? Who should own this shift—OEMs through design changes, or utilities through revised specifications and loading practices?
Q1.08: How can utilities and manufacturers standardize life cycle assessment methodologies to allow meaningful comparison between transformer technologies, refurbishment strategies, and insulating systems?
Q1.09: What is the optimal balance between refurbishment, life extension, and replacement strategies when considering carbon footprint, manufacturing lead times, operational efficiency, and long-term asset reliability? What are the key technical, operational, and economic barriers to wider adoption of low-carbon transformer technologies and sustainable manufacturing practices?

PS2: POWER TRANSFORMER DIGITALISATION JOURNEY

The subject covers:

- User experiences, challenges and solutions with transformer data management: data collection, processing, exchange with different stakeholders/systems, confidentiality and security.
- Innovative digital solutions for monitoring, diagnostics, modeling, designing, manufacturing, testing, maintenance and operation of transformers.

A total of 28 papers were submitted on this preferential subject, of which 20 were selected for the special report. These 20 were further categorized into the following subtopics;

- PS2-1: Digital Twins and Advanced Asset Lifecycle Management (7 papers).
- PS2-2: Monitoring, Diagnostics and Data-Driven Condition Assessment (9 papers)
- PS2-3: Modelling, Simulation and Thermal-Hydraulic Analysis (4 papers)

PS2-1: Digital Twins and Advanced Asset Lifecycle Management

Paper 10207 (India) presents the development of a Digital Mirror platform for power transformers and reactors, combining enterprise records, SCADA data, online monitoring, diagnostic tests and hybrid physics-AI analytics to continuously evaluate asset health, ageing, failure probability and operational risk. The system integrates health, thermal, ageing and impact models into a unified risk-based maintenance framework, demonstrating improvements in transformer availability and reductions in maintenance effort.

Paper 10220 (USA) presents an AI-boosted life management framework that combines technical knowledge bases, transformer operational databases and large language model (LLM)-based artificial intelligence engines to support asset management decisions. The proposed architecture integrates established transformer knowledge from CIGRE, IEEE and operational experience with historical asset information to enable condition assessment, risk ranking, failure prediction and maintenance recommendation generation through natural-language interaction.

Paper 10385 (Australia) describes a digital twin framework for transformer moisture management integrating dual-probe online monitoring, cloud-based analytics, machine-learning algorithms and automated dehydration systems. The proposed solution continuously monitors insulation moisture conditions, detects abnormal moisture behavior and automatically optimizes transformer dry-out processes to improve insulation reliability and extend asset lifetime.

Paper 11054 (Italy) discusses the application of Building Information Modelling (BIM) methodologies to transformer digitalization projects, integrating engineering, construction, operational and maintenance information into a unified digital platform. The contribution highlights how BIM approaches improve collaboration, asset traceability, lifecycle data management and infrastructure coordination for transformer installations.

Paper 11489 (Republic of Korea) develops a partial discharge diagnostic system based on a digital twin with a 3D physical representation of the transformer. Using geometric models and material properties, it simulates the propagation of UHF signals, allowing for optimized sensor placement and the location of discharge sources.

Paper 11862 (Canada) presents a comprehensive digital twin development initiative for a utility, based on multi-state degradation models that integrate different transformer subsystems (insulation, oil, bushings, OLTC, etc.). Physical models, historical data and AI techniques (including deep learning and vibroacoustic analysis) are combined for diagnostics and prognosis. Advanced DGA interpretation tools and aging models are also addressed, creating a holistic platform for fleet-level condition assessment.

Paper 11987 (Austria) analyzes the use of a thermal digital twin to optimize transformer loading in grid operation. Unlike static methods, the model considers real-world conditions (ambient temperature, cooling status, tap changer, load history), allowing for the dynamic calculation of overload capacity without exceeding thermal or aging limits. It demonstrates significant potential for improving asset utilization and integrating renewable energy sources.

A total of 7 papers were reviewed under this subtopic, covering the growing role of digital twins and mirrors, large language models, BIM platforms, advanced analytics and integrated monitoring systems for transformer asset lifecycle management. The papers highlight how utilities and manufacturers are increasingly combining online monitoring, physics-based modelling, AI/ML techniques and immersive visualization tools to improve condition assessment, maintenance optimization, operational reliability and lifecycle decision-making. The papers submitted under PS2-1 demonstrate the rapid evolution of transformer asset management from conventional condition monitoring towards a fully integrated digital lifecycle management system. A recurring theme across the contributions is the increasing convergence of operational monitoring, diagnostic analytics, asset databases and predictive modelling into unified digital platforms capable of continuously reflecting transformer condition and operational risk.

Another important trend is the growing use of hybrid analytics approaches that combine physics-based transformer models with AI and machine learning techniques. Rather than relying exclusively on black-box predictive algorithms, some of the papers emphasize the value of combining established transformer engineering principles with data-driven anomaly detection and pattern recognition methods.

At the same time, the papers raise important challenges regarding data quality, model validation, cybersecurity, interoperability between platforms and the practical integration of digital tools into utility operational processes. As digitalization accelerates, ensuring transparency, scalability and engineering trust in these systems will become increasingly important for utilities and manufacturers alike.

Q2.1: What are the main challenges associated with validating digital tools outputs and ensuring engineering confidence in automated maintenance or operational decisions?
Q2.2: Should digital twin technologies primarily focus on improving operational efficiency and maintenance optimization, or should they evolve toward fully autonomous asset management and intervention systems?
Q2.3: How can utilities establish interoperable data architectures and common information models to ensure scalability and avoid vendor lock-in in digital twin ecosystems?

PS2-2: Monitoring, Diagnostics and Data-Driven Condition Assessment

Paper 10148 (France, China, USA) analyzes the accuracy of sensors integrated into digital bushings that measure current and voltage. Effects such as temperature and phase coupling are evaluated, demonstrating that these sensors provide reliable digital data for monitoring transformers in digital substations. Critical factors such as proper calibration and the measurement environment are also highlighted.

Paper 10149 (France) discusses approaches for enhanced transformer diagnostics using integrated operational and monitoring data, emphasizing the use of continuous condition assessment and analytics-based interpretation to improve reliability and lifecycle management.

Paper 10209 (India) presents an artificial intelligence-based framework for assessing the condition of transformers and reactors, focusing on dissolved gas analysis (DGA). Machine learning and deep learning techniques (LSTM, GRU, ARIMA) are used to predict failures and estimate insulation aging. The system includes a resampling engine to handle irregular data and generates a health index (HI) as a global indicator of the asset's condition. The results demonstrate a significant improvement in predictive capacity compared to traditional methods.

Paper 10706 (South Africa, Argentina, France, Slovenia, Germany, Canada, USA, Austria, Croatia) proposes a standardized XML-based digital data model intended to support the structured capture, exchange and lifecycle management of transformer information. The proposed schema separates transformer information into assets, operating states and system properties, enabling flexible representation of both static and operationally dependent parameters throughout the asset lifecycle. The work highlights the importance of interoperability, version control, traceability and extensibility in supporting digital twins, condition monitoring systems and future data-driven asset management applications.

Paper 10707 (South Africa, United Kingdom, India) presents AI and machine-learning methodologies for adaptive transformer diagnostics using online DGA data and contextual metadata. The paper introduces modified normalized energy indices (NEI) and unsupervised deep-learning approaches to establish transformer-specific alarm baselines and improve anomaly detection while reducing nuisance alarms.

Paper 10762 (Japan) presents an IoT-based monitoring system designed for mass deployment in substations without requiring modifications to existing transformers. The system monitors key variables such as temperature, current, hydrogen (DGA), tap position and oil leaks, providing real-time data for condition-based maintenance (CBM). Its low cost and high scalability are also highlighted.

Paper 11885 (Croatia) presents a unified digital platform for the complete automation of transformer testing processes (test bay), encompassing the pre-test, test and post-test phases. The solution integrates test setup, automatic data acquisition, standards-compliant processing (IEC/IEEE) and traceable report generation, all within a centralized digital environment. Digitalization improves efficiency, reduces human error and ensures consistency and traceability of results, while also laying the groundwork for advanced applications such as lifecycle analysis, in-service monitoring and the development of digital twins.

Paper 11985 (Austria, France) A wireless monitoring system for air-core dry reactors is described, based on autonomous sensors powered by the reactor's own magnetic field. The system measures vibration, magnetic field, temperature and acoustics, storing data on a local system. Its field viability and ability to provide useful information for predictive maintenance through trend analysis and correlations between variables are demonstrated.

Paper 12405 (Germany) introduces the concept of an OLTC digital fingerprint using vibroacoustic measurements during factory testing. These signals allow for the detection of mechanical wear and anomalies by comparison with statistical references. The creation of reference databases for in-service monitoring is proposed, facilitating objective, data-driven diagnostics.

A total of 9 papers were reviewed under PS2-2. They have shown advancements in how transformer and reactor monitoring and diagnostics are approached, driven by digitalization and the systematic use of data. Throughout the work, a clear expansion of the traditional scope is observed, moving from approaches focused solely on isolated measurements or periodic tests to an integrated vision that covers the entire asset lifecycle, from data generation at the factory to its use in operation.

One of the most relevant trends is the digitization of data at the source and its structuring throughout the entire process. The need for reliable, traceable data in interoperable formats, both during testing and operation, is emphasized as an essential foundation for any subsequent analysis. In this regard, two complementary perspectives emerge: on the one hand, an approach more focused on processes and information systems, aimed at standardizing and automating data generation and exchange; On the other hand, there is a perspective more closely linked to engineering, which emphasizes the creation of physical references and "digital fingerprints" of the behavior of the equipment for future comparison.

In parallel, significant progress is evident in monitoring systems, which are evolving towards distributed, non-intrusive and massively deployable solutions. These systems allow for the continuous measurement of multiple physical variables—electrical, thermal, mechanical or chemical—with high temporal resolution, providing a much richer view of the real-world behavior of assets. However, within this field, different approaches coexist - some prioritize scalability and low cost, facilitating implementation in large fleets, while others focus on obtaining more detailed multiphysics information, albeit with greater complexity.

Ultimately, all the work converges on the advanced exploitation of data through analytical techniques and adaptive models, including artificial intelligence and machine learning. A clear transition is observed from diagnostic methods based on fixed rules to models capable of learning from the historical and specific behavior of each asset. Nevertheless, different perspectives are also emerging, ranging from approaches focused on quantitative prediction and the generation of global indicators, to models that integrate context and metadata to adapt the diagnosis to the characteristics of each sub-component of equipment. Overall, these papers reflect the evolution towards a paradigm in which data, properly structured and analyzed, allows progress towards predictive maintenance strategies and optimized asset management.

Q2.4: What balance should be maintained between traditional engineering expertise and AI-driven anomaly detection when interpreting online monitoring and DGA results?
Q2.5: What are the main barriers to integrating factory testing, online monitoring, operational data and maintenance records into unified transformer condition assessment platforms?
Q2.6: How can utilities ensure data quality, contextual consistency and cybersecurity while integrating heterogeneous monitoring and operational datasets into AI-driven diagnostic platforms?
Q2.7: As transformer digitalization matures, what should be the roadmap for progressing from monitoring-driven systems toward autonomous and self-optimizing asset management ecosystems?

PS2-3: Modelling, Simulation and Thermal-Hydraulic Analysis

Paper 11094 (Portugal) investigates the thermal-hydraulic behavior of shell-type power transformers operating with alternative insulating liquids under OD and ON cooling modes. The paper evaluates the influence of fluid properties on thermal performance and flow distribution using numerical modelling approaches.

Paper 11092 (Portugal) details the development of a dynamic THNM for core-type transformer windings. The model combines detailed hydraulic and thermal representations with significantly reduced computational effort compared to CFD simulations.

Paper 11093 (Portugal) discusses the use of advanced digital modelling techniques for dissociated-phase shell-type phase-shifting transformers. The work focuses on the simulation of internal overvoltages, core overexcitation phenomena and multi-terminal lightning impulse testing using high-frequency digital models.

Paper 10270 (Netherlands) presents the implementation of a Dynamic Transformer Rating methodology for large three-winding transformers in the Dutch transmission grid. The contribution extends IEC 60076-7 thermal models through an open-source Python-based Transformer Thermal Model (TTM), including three-winding transformer behaviour, ONAN/ONAF cooling transitions and tap changer dependency.

A total of 4 papers were reviewed under PS2-3, focusing on the development, application and validation of numerical and analytical models for characterizing the thermal-hydraulic behavior of power transformer windings. The papers span the full modelling spectrum — from detailed Computational Fluid Dynamics models to reduced-order Thermal-Hydraulic Network Models (THNM) and system-level IEC-based thermal models — and collectively address both core-type and shell-type transformer architectures. A common thread is the drive to translate modelling advances into operational tools capable of supporting real-time monitoring, dynamic rating and transformer digitalization, while also informing the adoption of alternative insulating fluids.

The papers in this group collectively reflect the progressive digitalization of transformer thermal analysis. Key shared themes include: the role of fluid thermophysical properties in determining thermal performance under different cooling regimes; the trade-off between model complexity, computational speed and accuracy needed for real-time deployment; and the validation pathway from laboratory tests to field data.

Q2.8: How should utilities and manufacturers validate advanced digital models used for transient, thermal and electromagnetic performance assessment under increasingly complex operating conditions?
Q2.9: What are the main challenges associated with integrating alternative insulating liquids and new cooling strategies into existing transformer thermal modelling standards and operational practices?

PS3: FAILURE PREVENTION; DETECTION AND INVESTIGATION

The subject covers:

- Detailed case histories of failures including examples such as component issues, short-circuits, moisture, dielectric breakdowns, paper degradation, material compatibility problems, etc.
- Guidelines for conducting investigations: Root Cause Analysis (RCA) including testing and troubleshooting procedures.
- Predictive maintenance: Best practices for monitoring, diagnostics, and prognostics.

A total of 50 papers were accepted under this Preferential Subject, addressing topics including DGA, partial discharge, silver corrosion, renewable energy applications, and a wide range of case studies. From these contributions, 21 papers were selected for inclusion in this Special Report and were classified under the three following subtopics:

- PS3-1: Case Studies and Failure Investigations (8 papers)
- PS3-2: Diagnostic Methods and Monitoring Techniques (9 papers)
- PS3-3: Failure Mechanisms and Emerging Risks (4 papers)

PS3-1: Case Studies and Failure Investigations

Paper 10145 (France) shows that transformers that have been validated only by calculation, have significantly higher failure risk when compared to units validated by short-circuit testing. The paper details a real fault case demonstrating the catastrophic failure of a calculated unit, meanwhile a tested sister unit remained intact. The study highlights major limitations of IEC 60076-5 calculation methods, including underestimation of stresses and concludes that full short-circuit testing is essential to ensure transformer reliability.

Paper 10150 (France) presents an online leakage-current algorithm that can be used to detect early RIP/OIP Bushing degradation. The algorithm identifies single-layer failures (~2%) using phase-deviation analysis and Z-score filtering to remove noise and false alarms. The method is also field-validated with high reliability and has prevented major transformer failures. The paper also highlights gaps in current standards, especially for GIS applications.

Paper 10272 (Netherlands) demonstrates that fiber-optic acoustic emission sensors can accurately locate dielectric breakdowns during transformer FAT Lightning Impulse (LI) and Switching Impulse (SI) tests. By analyzing time-of-arrival of acoustic signals, fault locations are identified with ~±0.5 m accuracy. This method enables direct localization during the initial failure, avoiding additional testing and damage. The results confirm strong potential for application as a standard monitoring tool in FAT to save time and resources.

Paper 11028 (Argentina) highlights that reliable assessment of 500 kV assets requires integration of on-line monitoring, off-line tests, and operational data. Case studies show that isolated diagnostics can miss or misinterpret faults, while combined analysis enables accurate fault identification. DGA is a key early indicator but must be correlated with other diagnostics. This approach improves maintenance decisions, reduces failure risk and minimizes the likelihood of misdiagnosis that could lead to unnecessary outages.

Paper 11029 (Argentina) presents a structured RCA methodology for wind turbine Transformers under highly demanding operating conditions. Failures are linked to combined effects such as inadequate specifications, FAT shortcomings, thermal cycling, harmonics, and ventilation issues. The approach integrates design review, operational data, testing, and post-mortem analysis. It enables identification of root causes and implementation of corrective actions to improve reliability.

Paper 11893 (Jordan) presents two failure cases combining DGA, electrical tests, and internal inspection to identify hidden defects. One case shows thermal faults caused by magnetic flux leakage due to a deformed tank shunt, while the second highlights cellulose aging driven by moisture and oxygen ingress. The study confirms that oil analysis detects issues early, but root causes require internal inspection. It recommends improved tank design, moisture control, and continuous monitoring to enhance reliability.

Paper 12093 (Malaysia) investigates bushing failures in GIS-connected and Reactor applications driven by VFTO and frequent switching. It shows that high-frequency transients, poor test tap grounding, and unsuitable breaker operation can cause localized electrical stress and arcing. Case studies confirm failures linked to VFTO, floating test taps, and insulation stress concentration in foil layers. The study recommends proper grounding, controlled switching, and transient protection to mitigate bushing failures.

Paper 12094 (Malaysia) analyses the degradation of polymeric (LSR) transformer bushings showing “alligatoring” cracking. The failure is linked to UV exposure, moisture, and manufacturing variability affecting curing and filler dispersion. Material analysis confirms oxidation, loss of hydrophobicity, and formation of a brittle degraded surface layer. The study concludes that LSR bushings are sensitive to process quality and recommends stricter manufacturing control, extended aging tests, and improved inspection practices.

Short-circuit withstand capability remains a major contributor to Transformer aging and end-of-life. Current IEC standards provide a structured framework; however, as highlighted in the contribution, limitations exist in the validation approach, particularly when based on calculation methods, which may not fully capture the actual mechanical stresses experienced during fault events. This aspect deserves further attention, especially under evolving grid conditions.

In parallel, an increasing number of fault cases are being observed in transformers used in renewable energy applications, such as those used in wind farms/wind turbines. The presented root cause analysis (RCA) methodology provides valuable guidance for systematically addressing these failures. Additionally, dry-type transformers are gaining importance in such applications and will be specifically addressed within a new working group on “Dry-Type Transformer Life Cycle Management.”

Furthermore, very fast transient (VFT) phenomena are increasingly reported across different transformer applications, with a clear correlation to the expansion of renewable energy systems and power electronics. These stresses can lead to insulation degradation and unexpected failure modes.

Fault investigations clearly demonstrate the importance of combining multiple diagnostics with field validation and investigation techniques. No single method is sufficient to fully understand complex failure mechanisms, and an integrated approach significantly improves the quality of the analysis.

Finally, bushings remain a critical component in transformer reliability. They continue to be strongly represented in real case fault statistics and must be considered a key element in both condition monitoring and failure prevention strategies.

Q3.01: How can Transformer designers and manufacturers proactively address emerging mechanical and electrical stress mechanisms? What validation need to be improved to consider the variety of stresses observed under real operating and fault conditions (Short circuit, VFT and renewable energy)?
Q3.02: How are evolving power systems creating new failure mechanisms in Power Transformers, and what are the challenges for transformer reliability in conventional grids versus renewable energy systems?
Q3.03: Looking ahead, which emerging stress mechanism - short-circuit forces, VFT, renewable operation profiles, or component degradation - is likely to have the greatest impact on transformer life expectancy?

PS3-2: Diagnostic Methods and Monitoring Techniques

Paper 10252 (India) investigates how to predict fatigue damage and vulnerability of Shunt Reactors. The paper shows that weld cracks in Shunt Reactors are caused by cumulative vibration-fatigue, even when vibration levels comply with standards. It presents an integrated method combining measurements, FEM and fracture mechanics to predict crack initiation and growth. Results confirm welded joints—especially weld metal—are the most vulnerable, with rapid crack propagation once initiated. The approach enables identification of critical zones at design stage and improved reliability.

Paper 10386 (Australia) shows through 4 different case studies, that moisture is a critical contributor to transformer failures. It reduces dielectric strength and makes units vulnerable to normal stresses such as cooling, switching, and faults. Traditional oil testing alone is insufficient, as relative saturation and paper moisture are key. The study emphasizes continuous monitoring and proper dry-out strategies and ultimately suggests that moisture is the catalyst that transforms routine networks events into failures.

Paper 11263 (Israel) evaluates the predictive value of Asset Health Index (AHI) models using real failure data. Results show strong variation: high-sensitivity models detect failures early but generate more false alarms, while conservative models miss early degradation. Incorporating rate-of-change indicators and tailored parameters improves early detection. The study recommends a layered approach combining AHI screening, diagnostic interpretation, and expert validation to avoid premature replacement of assets.

Paper 11269 (South Africa) presents an improved tap changer condition monitoring approach based on DGA to support predictive maintenance. The method enhances detection of abnormalities but struggles to identify fault type and severity. Case studies show that both false alarms and missed failures can occur due to limited diagnostic accuracy. The paper concludes that more data and experience are required to refine reliable diagnostic criteria.

Paper 11508 (United Kingdom, Germany) analyzes a large DGA database (5500 units) of synthetic-ester Transformers in wind applications. It proposes a traffic-light threshold system (green/yellow/red) based on 90th, 95th, and 98th percentile averages. Results show this approach is more conservative and provides earlier warning than standard 90th percentile limits. The study concludes that DGA thresholds should be fleet-specific rather than relying solely on standard limits.

Paper 11984 (Austria) shows that combining classical DGA interpretation techniques with AI-based methods improves transformer diagnostics. Classical methods detect faults once thresholds are exceeded, while AI identifies early anomalies from subtle gas trending. The study demonstrates that a hybrid approach using both traditional DGA interpretation with anomaly-based modals enable earlier detection and support predictive, risk-based maintenance.

Paper 11991 (Austria, Germany) proposes a systematic Partial Discharge based approach for condition assessment of dry-type Transformers, addressing the lack of DGA applicability. It combines PRPD patterns, PDIV/PDEV ratios, polarity analysis, and charge levels to classify internal vs external discharges and evaluate risk. A scoring method integrates these factors to support operational decisions and preventive maintenance.

Paper 12337 (Germany) investigates condition assessment of transformer paper insulation, using degree of polymerization (DP) as the key ageing indicator. It shows that indirect methods based on 2-FAL can estimate average DP but have limitations, especially after oil treatment. Methanol is identified as a sensitive early ageing marker, while ethanol indicates thermal stress. The study proposes a novel optical sensor enabling direct, real-time DP measurement with strong correlation to laboratory values, improving condition-based maintenance.

Paper 12431 (Germany, Australia, Austria) presents modern diagnostic techniques for transformers connected to renewable energy sources. This study shows that transformers under renewable integration require advanced monitoring (FRA, UHF-PD, OLTC, fibre-optic temperature) due to dynamic loading increasing stress. These methods enable earlier fault detection and better thermal assessment, supporting a shift from time-based to condition-based maintenance, and enable data-driven decision-making in Transformer management.

Dissolved Gas Analysis (DGA) remains a basis for transformer condition assessment. Several contributions confirm its continued relevance, demonstrating its ability to detect early-stage faults that may not be identified by conventional electrical testing alone. In particular, DGA provides valuable diagnostic insight when interpreted in combination with operational data and complementary diagnostic methods, reinforcing its role as a primary tool for asset evaluation.

At the same time, new knowledge is being developed for specific applications such as on-load tap-changers (OLTC) and transformers filled with alternative insulating liquids, such as synthetic esters. Case studies highlight that DGA interpretation in these applications requires adapted approaches, as characteristic gas patterns, threshold values, and diagnostic methods are still evolving. This underlines the importance of building experience and establishing application-specific expertise to ensure reliable interpretation.

With regard to asset management, Asset Health Indexing (AHI) methodologies remain used to support decision-making processes. However, recent developments show a growing integration of advanced data analytics and artificial intelligence (AI) models. These approaches enable improved trend evaluation, anomaly detection, and prioritization of assets requiring attention, indicating a gradual shift toward more data-driven and predictive maintenance strategies.

In parallel, partial discharge (PD) detection techniques continue to evolve, particularly for dry-type transformers. The increasing deployment of renewable energy systems introduces new operating conditions and stress profiles, driving the need for more sensitive and robust PD monitoring solutions. Advanced methods, such as UHF-based detection, demonstrate improved capability for fault localization and operation in electrically noisy environments, supporting reliable condition assessment in these applications.

Overall, the contributions illustrate a clear trend toward combining proven diagnostic techniques such as DGA with emerging technologies, including AI and advanced monitoring systems. This integrated approach is essential to address the increasing complexity of transformer operation and to ensure reliable asset management in modern power systems.

Q3.04: How do traditional approaches such as Dissolved Gas Analysis (DGA) and Asset Health Index's maintain their relevance in modern transformer condition assessment despite the development of newer diagnostic technologies. To what extent can AI-based models improve or replace these methods?
Q3.05: How can existing diagnostic techniques be adapted to ensure reliable condition assessment in applications such as OLTC, ester-filled, dry-type transformers or renewable applications like wind turbine?
Q3.06: What might the future of transformer asset management look like if predictive analytics, intelligent monitoring systems, and real-time diagnostics become fully implemented. What are the potential benefits and challenges of developing fully integrated transformer monitoring systems that combine DGA, PD analysis, operational data, and AI?

PS3-3: Failure Mechanisms and Emerging Risks

Paper 11279 (United Kingdom) analyses transformer and reactor failure investigations over more than a 20-year period, identifying main failure modes, locations, and causes. It shows dielectric failures dominate and highlights tap changers and windings as key failure locations. Among diagnostic methods, liquid tests (DGA) are most effective for early indication, while SFRA and electrical tests are strongest for fault identification. The paper recommends a structured approach combining visual inspection, liquid analysis, and targeted electrical testing.

Paper 11719 (Canada) presents three transformer short-circuit failure cases showing severe mechanical damage such as winding collapse, buckling, and telescoping. Short-circuit forces can cause catastrophic LV winding failures, while HV winding often remains intact. Hidden damage such as buckling may persist for years before failure. Improved materials and FEM-based design significantly enhance short-circuit design technology and reliability, for new transformers and repair of failed transformers.

Paper 12318 (Serbia, Germany, Finland, Spain) shows that silver corrosion in synthetic ester filled transformers is driven by very low levels of elemental sulfur (S_8, <1 ppm). Standard corrosion tests may underestimate the risk due to non-representative conditions and silver strip corrosion tests were found to be inadequate. The study confirms faster silver sulfide formation in esters than in mineral oil. An on-site treatment successfully removed sulfur, eliminated corrosivity, and improved oil properties without impacting DGA or dielectric performance.

Paper 12349 (Serbia) shows that DGA performed during no-load tests can detect thermal and electrical defects in the magnetic core that standard electrical measurements miss. Even under no-load conditions, small amounts of gases (especially acetylene) indicate core faults or local overheating. Case studies confirm that DGA can reveal hidden defects despite normal FAT results. The paper recommends extended no-load energization with DGA as a sensitive, non-intrusive diagnostic tool.

The contributions confirm that transformer failures remain largely dominated by dielectric mechanisms, with tap changers and windings identified as critical locations. Field experience further shows that failures often result from a combination of electrical, thermal, and mechanical stresses rather than a single root cause.

A key observation is that mechanical stresses, particularly following short-circuit events, can introduce hidden damage such as winding deformation. These defects may remain latent for extended periods before developing into critical failures, highlighting the importance of considering delayed effects in condition assessment.

In addition, material-related degradation mechanisms are observed in specific applications. In synthetic ester-filled transformers, silver corrosion driven by very low levels of elemental sulfur has been identified, with silver sulfide forming more rapidly than in mineral oil. Practical experience shows that targeted on-site treatment can effectively mitigate this issue.

Finally, several cases demonstrate the limitations of conventional electrical testing in detecting certain types of defects. Extended no-load energization combined with dissolved gas analysis (DGA) proves to be a sensitive and non-intrusive diagnostic approach, capable of detecting early-stage faults and hidden defects that may otherwise remain undetected.

Overall, the contributions highlight the increasing complexity of transformer failure mechanisms and the need for integrated diagnostic approaches to reliably detect and interpret such conditions.

Q3.07: How should future transformer condition assessment strategies evolve to account for hidden defects, delayed degradation, and emerging material-related issues. How can advanced or complementary diagnostic approaches support early detection?
Q3.08: What lessons can be learned from silver corrosion in synthetic ester-filled transformers regarding unintended consequences of adopting alternative insulating materials? To what extent can targeted on-site treatments be considered a sustainable long-term solution compared with redesigning materials or system components?
Q3.09: How does the interaction between electrical, thermal, and mechanical stresses challenge the traditional approach of identifying a single root cause for transformer failures? Given the growing complexity of these mechanisms, what characteristics should an ideal integrated diagnostic framework possess?
Q3.10: What makes tap changers and windings particularly vulnerable locations for failure, and how might future designs reduce these vulnerabilities? Should maintenance strategies prioritize high-risk components such as windings and tap changers over uniform inspection practices?