A2 - 00

SPECIAL REPORT FOR SC POWER TRANSFORMERS AND REACTORS

PS1	PS2	PS3
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Special Reporters

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1 Scope of Study Committee A2: Power Transformers and Reactors

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,

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- Reliability, availability, dependability, maintainability and maintenance, service, condition monitoring, diagnostics, restoration, repair, loading, upgrading, uprating,
- Refurbishment, re-use/re-deployment, deterioration, dismantling, disposal.

2 Group discussion meeting 2024 Session

The A2 Group Discussion Meeting during the next session will take place from **8h45 to 18h00 on Friday August 30th, 2024, at l'Amphithéatre Bleu**.

All intended contributors should first finalise their registrations before they can propose a contribution. Proposed contributions should be uploaded on the session Registration Portal by the authors **no later than August 10th, 2024**. All contributions will be reviewed by the Special Reporters and the Study Committee Chair based on their relevance to the Preferential Subjects and the questions in the Special Report. Final acceptance will be communicated on August 16th, 2024.

Presentation of each contribution at the Group Discussion Meeting is typically scheduled for about 3-5 minutes. Please prepare accordingly by:

- Limiting the number of slides to about five,
- Keeping introductory remarks to the minimum,
- Sticking to the question from the Special Report,
- Presenting your conclusions (answer to the question) immediately after your title slide and using the following few slides to substantiate your answer.

All accepted contributors are required to meet shortly with their Special Reporter on August 29th, 2024 (the day before the Group Discussion Meeting) anytime between 8h45 and 12h00. The purpose of this short meeting is to review the final details of their contribution and to receive the latest instructions (such as schedule).

For further details and possible updates on the session, please consult the CIGRE 2024 website.

3 Preferential Subject 1 (PS1): Design of resilient transformers

The subject covers:

- Stresses from the environment: Impact of global warming, high temperatures heavy rain, high winds, offshore installations, etc.
- Stresses from the system: switching impulses, reverse flow, emergency overloading, harmonics, GIC, short-circuits and internal arcing etc.
- Specifications: design criteria, materials and testing requirements for new transformers. Suitable maintenance standard and refurbishment strategies.

A total of 37 papers were accepted. All papers were assigned to the following subtopics:

- PS1-1: Stresses from the environment (2 papers)
- PS1-2: Stresses from the system (18 papers)
- PS1-3: Materials, testing and others (17 papers)

3.1 PS1-1: Stresses from the environment

Paper 10259 (France, India, Turkey, Germany, China, United States) This paper provides an overview of the ongoing developments in qualifying power transformers and shunt reactors for floating offshore applications. Drawing from the experience gained with fixed bottom offshore substations, the study analyses critical components and potential failure scenarios. Calculations and tests were conducted to address identified gaps.

Paper 11237 (Japan) introduces examples of both preventive measures, such as design considerations and innovations to minimise damage to large transformers, and post-earthquake measures to accurately determine their integrity in order to ensure the resilience of power systems in the event of an earthquake disaster.

3.2 PS1-2: Stresses from the system

Paper 11284 (India) provides firsthand experience in operational and maintenance experience of variable shunt reactors. It has been shown that the voltages in the grid are lower after the installation and some interesting ideas on how to use OLTC are presented, to minimize the number of switching operations of a circuit breaker.

Paper 11677 (Croatia) presents simulation of a transformer winding using an RLCM model and checking the effect of number of branches on the model accuracy. The outcome of the paper is making the usage of model aware on the number of branches. This helps to apply the model even for non-standard voltage waveshapes.

Paper 10785 (Russian Federation) provides valuable insights in nonstandard transients that occur in the power network. A modification to the existing TDSF method (called TDSI by the authors) is presented in the paper. Moreover, the paper describes a system that can do online transient monitoring. The contribution starts with a new method to evaluate the ratio between dielectric stress and strength for inter-coil winding insulation based on integral method. Additionally, this new approach is demonstrated on the practical case of hydroelectric power plant. Finaly, a monitoring system for high-frequency recording is presented and the main challenges are discussed for measurement of transient overvoltages on electrical power equipment in operation.

Paper 10122 (United States) discusses the necessity of front chopping of lighting impulse (FOW) impact on the inner winding insulation. Such waveshape triggers highly non-uniform overvoltage distribution along the winding. Therefore, it is questionable if the conversion factor often used between FOW and FW is accurate enough. The paper describes the impact of this special test for the dielectric design of transformers and gives the recommendation to cover the FOW test by a higher Basic Insulation

Level (BIL). In addition, a comprehensive analysis including measurements and simulations is performed for a failure event which is associated with a FOW test on medium power transformer.

Paper 11156 (Germany, Austria) analyses pressures resulting from an arcing fault in the oil compartment of an OLTC using CFD and explicit dynamics method. It is closely related to the ongoing CIGRE Task Force "Power transformer tank specification for passive protection against internal arc" which aims to collect the current knowledge of the whole transformer industry with respect to adequate requirements for the tank design including accessories. The new design shows that in the case of internal arc in OLTC compartment that the bottom of the OLTC compartment will fail before the cover, which minimizes safety risks. This is a paper of interest as an OLTC is an important tank accessory that must be able to withstand the effect of an arc.

Paper 10148 (China) Comparison of arc failure inside the lead exit of a UHV AC transformer. Two different designs are studied - traditional lead out from tank and embedded lead out. It is shown that the embedded solution is much more resilient to an arc occurrence.

Paper 10157 (China) Calculation of resistivity of design during internal fault for different transformer components (transformer tank, bushing ascending flange and on load tap changer) is carried out in the paper. The paper presents also experimental verification of results on actual components.

Paper 10840 (Canada) presents the evolution and update of the tank rupture FEM simulation methodology also with requirements for accessories from a utility view. It brings detailed instructions on the procedure how to calculate including mesh size and zone specifications.

Paper 10543 (Spain) contributes to the important topic of assessing the capability of shell type transformers to withstand short circuits and in particular the dynamic effects. This is a very difficult topic, and the contribution adds some important possible techniques to the simplification of the dynamic modelling and introduces some material tests of relevance. The accuracy of the simplified model is tested favourably against a full 3D model. Testing against a physical model is in further work so evaluating the real-world accuracy has yet to be done. There is an attempt to simplify the use of the model using an artificial neural network, but there is little detail on how this was done and so it is hard to evaluate. The possibility for generalization to core form transformers is not clear.

Paper 10149 (China) presents an analytical method of calculating axial and radial stress on a conductor at a parallel cable transposition where both the radial and axial positions of the conductor are changed. This is a potential weak point in any winding with parallel conductors that are transposed at particular places in the winding. The paper therefore highlights an important problem in assessing the short-circuit strength of a winding. The analysis is limited to the direct stresses on the conductor assumed to be mechanically a beam supported rigidly at both ends. The paper does not therefore address the hoop buckling mode of failure that can also occur at mechanical weak points. The correlation between the analytical results and an FEM model is impressive.

Paper 11753 (Croatia) has presented 3D FEM approach to calculate and visualize forces on leads during short circuit. The case study shown considers large offshore transformers with axially split dual MV windings.

Paper 10712 (Switzerland) analyzed the results of short circuit testing on several transformer units. All the presented units passed the test requirements according to IEC. The tests have been done on used units as well. It is necessary to discuss if such testing could provide useful information to improve transformer reliability if done on a test samples withing population of a distribution transformer each 10 years in service. Moreover, an interesting negative change in short circuit impedance has been observed for a single transformer unit, after short circuit test. The paper discusses the practical outcome of short circuit tests on transformers of up to 1MVA. It is interesting because it includes testing of transformers that have been in service for some years. It is in the form of a set of case studies rather than an experiment or investigation, but it provides an interesting basis for discussion. In particular, the reports of a reduction in impedance following test are the basis for further work.

Paper 10733 (Republic of Korea) shows the results of a GIC test with a mock-up transformer and the simulation of the measured effects with a reluctance network model. It shows that a reluctance network model simulates the flux behavior in affected components during DC well. In addition, also the measured temperatures have been re-simulated with a model and compared with the measured ones in the paper.

Paper 10784 (Russian Federation) describes a resistive-thyristor neutral grounding system for the protection of power transformers from the effects of geomagnetic storms. DC limiting resistors are bypassed by a parallel pair of thyristors if the saturation detection system does not detect core saturation. Saturation detection is based on the measurement of the DC component and harmonics in the neutral current by means of a hall effect sensor with subsequent low pass and band pass filters.

Paper 10886 (Norway, Germany, Sweden) evaluates and verifies the extent of geomagnetic induced currents (GIC) effect on power transformers considering two critical core designs and tertiary winding influence. Part 1 describes the necessary characteristic of transformer designs, corresponding modelling that results in predetermined sensor locations, installed instrumentation, data acquisition system, factory and site testing setups and safety conditions as well as determination of testing sequences.

Paper 11033 (Germany, Sweden, Norway) is part 2 of the paper 10886. The contribution gives results of an experimental DC measurements on a 3-limb and 5-limb in-service transformers. This is a good input towards specifying GIC withstand capabilities for transformers of different limb designs.

Paper 11843 (New Zealand) presents the results of an on-site DC injection test. Such tests are quite rare. The ground return current in monopole operation of an HVDC link was used to produce DC currents in the grounded neutrals of nearby power transformers. Up to 35 A DC were measured in the neutral of one of the three-limb, three-phase 216 MVA autotransformers, with effects on sound level, vibration and current harmonics starting at DC currents > 25 A.

Paper 10517 (Netherlands, United States) shows the results of a GIC experiment in the power grid with two single-phase transformers in Back-2-Back connection. The transformers have an independent clamping design, which has the tie rods on the outside of the windings. The paper points out that in such designs the tie bars are not affected by DC/GIC and other components like the core yoke clamp show the highest temperature rise under DC, but lower as in other designs. In addition, the observed voltage and current distortions in the grid during the GIC field test are discussed.

3.3 PS1-3: Materials, testing and others

Paper 11352 (France) provide justification of EDF procurement specifications for new investments in renewing transformer fleet. The information provided can be groundwork for the procurement process for TSOs, taking into account extreme weather events and new ENTSO-E code.

Paper 10660 (South Africa) provides experience of reaching an acceptable resilience from a transformer from the TSO's perspective. It gives short case studies to justify the requirements for document specification, design and manufacturing, operation and maintenance, rewinding, refurbishing, and retrofitting and other.

Paper 10936 (Mexico, United States) presents experience with grid ready flexible transformer unit, which is in service for two years without any difficulty. Transformer unit is capable of changing short circuit impedance on load and it is equipped with state-of-the-art monitoring system.

Paper 11854 (Italy) presented modelling of dual-core phase shifting transformer in software for calculating transients. Introduction of PSTs in the power network ensures safe operation with increasing amount of renewables in the system. Simulation results have been taken into account during the design of the magnetic circuit of PST.

Paper 10546 (Canada, Norway, Spain) presented valuable case studies for transformer refurbishment and gave indications how to decide when to refurbish transformers. This is a hot topic today due to high demand for power equipment. It demonstrates that extending the lifespan of transformers is feasible, achievable, and sustainable amid the current widespread expansion of the electrical grid. It presents instances where parts were replaced either on-site or in a factory, with the majority of materials being reused, leading to significant reductions in CO_2 emissions for the transformers.

Paper 10489 (Sweden) discusses testing of large shunt reactors, which are used to compensate offshore cables. International standards like IEC and IEEE allow some compromises in the testing of large shunt reactors, where single-phase testing or testing with reduced power may be approved in an agreement between customer and reactor manufacturer. The paper elaborates if alternative test methods are reliable and accurate enough.

Paper 11282 (India) presents a real case of transformer failure during IVPD measurements, after passing short circuit testing. In IEC standard, it is not clear whether IVPD should be done after re-tanking the transformer. This example, however, shows a need for that, to avoid more costly failure of transformer at site.

Paper 10714 (Switzerland, Poland, Germany) presents benefits of using advanced insulation systems in terms of thermal transformer performance. Such design improvements can affect transformers overloading capability and consequently improve resilience of the transformer and power system or lower the transformer weight. Several case studies are presented, which provide indication of possibilities for overloading.

Paper 10611 (Poland, Switzerland, United States, Austria, Germany) presents possibilities to make more resilient transformer, such as using aramid insulation, alternative fluids, plug-in bushings, and flexible voltage ratings. With these technologies it is possible to achieve better dynamic thermal loading capability. more reliable transformers in operation and reduce maintenance and installation time. The work is relevant for large electrical companies, where a fleet of transformers with specified characteristics has been determined. In this case, you can allow the use of expensive mobile transformers as a backup.

Paper 10659 (South Africa) analyses how the nonstandard lightning impulses affect voltage distribution in the layer winding. As a possible solution for a resilient power transformer authors suggest electrostatic shield. The study shows that by controlling the capacitance between layers of the transformer insulation, the response on lightning distribution can be controlled and insulation can be optimized to increase lightning response and minimize failure of the insulation.

Paper 10351 (Italy, Germany) describes the approach and effort to meet the future challenges of increasing steel production under tightened environmental constraints. Transformer, tap-changer and liquid manufacturer present adequate solutions which are the result of thorough considerations, calculations and tests. Design rules for vacuum-type tap-changers for furnace applications in closed environment are given.

Paper 10402 (United Kingdom, Netherlands, Switzerland, Germany) discusses some aspects of thermal and insulation designs of transformers when considering different insulating liquids, i.e. a conventional mineral oil, a GTL oil and a synthetic ester liquid. Both experiments and modelling are carried out to provide creditable results and discussions.

Paper 11136 (United Kingdom, Jordan) provides practical information about mineral oil and synthetic esters parameters from actual transformers in service. The paper provides results of dissolved gasses, break down voltage, colour and other parameters.

Paper 10256 (France) presents different criteria/specifications to be taken into account, from a transformer manufacturer point of view, to validate an insulating liquid in terms of physical, chemical and dielectric properties. Safety and environmental impact requirements are also taken into consideration.

Paper 11857 (United Kingdom) provides an insight into the performance of ester liquid-impregnated Kraft paper through experimentally investigating the space charge dynamics and conductivity under DC fields and ageing. The study focused mainly on the influence of cellulose degradation. Kraft paper samples of different DP impregnated with fresh synthetic ester liquid and fresh mineral oil were prepared.

Paper 10545 (Spain) describes the experience gained and the results obtained in the development of a single transformer design which can be filled, depending on the location where it will be installed, with either mineral oil or oil from bio-based hydrocarbon liquids.

Paper 10150 (China) presented 10 kV oil immersed transformer model based on embedded electromagnetic wire. Winding deformation test method based on Brillouin optical time domain reflectometry technology is presented. The paper provides a possible method to monitor transformer winding deformation during short circuit testing or presumably in the future during service.

3.4 3.4 Discussion and Questions for Preferential Subject No 1

Upon reviewing the papers, the following discussion points and questions emerged regarding Preferential Subject No. 1.

Discussion for PS1-1: Stresses from the environment

Regardless of the huge growth of the offshore sector and importance of those for future energy sources, only one paper (10259) talks about development of offshore transformers, but in this case for future floating platforms. Testing methods to verify designs are described. Paper 11237 is looking at the influence of seismic activity on transformers – practical measures for transformer design and also checklist what to do after an earthquake.

<u>Question 1.1:</u> How to proactively prepare for extreme conditions (offshore, weather, earthquakes, etc.) both in design stage and operationally?

Discussion for PS1-2: Stresses from the system

High share of renewable energy in the power system may lead to high voltages, especially in the area where there is no consumption. To be able to control voltages, variable shunt reactors are installed. Maintenance and operational experience of such devices is valuable as the need for them is growing. Transients that occur in the power system differ significantly from the test impulses. The papers discuss nonstandard transients and how to evaluate their effect on the internal transformer insulations and to make transformer resilient to withstand such overvoltages. This is still an open topic as no standardized method exists to compare two waveforms (nonstandard and standard ones). Additionally, transformer manufacturers should have software for overvoltage calculations which can take non standards impulse into account, as a key element to make resilient transformer.

Explosion prevention is an important topic still requiring experimental verifications to verify numerical approaches. Great effort is invested to improve the calculations models and develop specifications to ensure an internal arc resistant design. From the paper from Canada it can be seen that the topic has reached a good maturity and standardization level.

Short circuit is severe event that can damage the transformer. To mitigate such a possibility, transformer manufacturers intensively work on developing suitable calculations for transformer adequate dimensioning. Nowadays, tools include 3D FEM software as well, not only analytics. However, testing transformer for short circuit is the ultimate proof that the transformer will sustain short circuit. One of the papers suggests that, for distribution transformers, testing have to be done after 10 years in service.
Research of geomagnetically induced currents (GIC) experienced a big improvement. The topic evolved from numerical calculations to small scale models and measurements on large units. Paper 10733 present measurements on a 2 MVA model transformer while 11843 and 10886/11033 describe experiments with 216 MVA and 1000 MVA respectively. With the verifications the knowledge is largely increased, and numerical methods are verified and calibrated. Paper 10784 presents a system to block DC current. With the release of the TB related to GIC and the latest results the topic seems to reach a peak and should become mainstream and not new anymore.

<u>Question 1.2:</u> How to monitor stresses during the lifetime of the transformer? How to define worse case scenarios?

Discussion for PS1-3: Materials, testing and others

To reach resilient design of the transformer, it is important to specify it correctly. Two papers speak about transformer specifications. Another important aspect of resilience is to conduct design review to challenge the calculations and transformer design. One of the papers presets a groundwork for the procurement process based on their own experience.

Transformers that can change short circuit impedance or have more different voltage levels that can be adjusted are considered as flexible transformers. Such transformers can be used on different locations in the power network. Big TSOs might have spare flexible transformer unit to be ready to replace existing units if necessary, in critical situations such as sudden failures. Additionally, PST units can be used to provide more flexibility in the power network.

Due to the fast pace of energy transition, refurbishment of power transformers is an option to extend the lifetime of the transformer. Compared to buying a new transformer, most of the components are reused, limiting CO2 footprint and reducing time needed to continue operations. This is a very important topic nowadays as transformer manufacturers lead time is enlarged due to the market.

To guarantee that the transformer is ready for service, substantial transformer testing has to be conducted. One of the papers discusses testing of large shunt reactors. According to IECT and IEEE standards, some compromises are allowed. Another paper speaks about IVPD testing on site, prior to the transformer installation. This is an important test that might ultimately test insulation of the transformer prior to putting in service.

The thermal performance of advanced insulation systems (i.e. aramid) can be valuable when improved resilience of transformer is required. The insensitivity of the insulation system to overheating can be a key in planning the overloading capability of transformers and calculating the dynamic thermal loading capability of the assets.

Insulating liquids remain a topic important for the design of transformers to ensure reliability and longevity. With increasing popularity of esters universal designs or specific designs to take advantage of esters are discussed. It can be seen that it is possible to use esters to improve the performance of transformers in special cases. Also discussed are material and liquid qualification. Ageing of liquids remains an interesting topic. There is a task force active that deals with silver corrosion problem in synthetic esters.

<u>Question 1.3:</u> How to ensure stresses are adequately incorporated in the design? What are the best practices from manufacturing and purchaser side (use of FEM, CFD, design review etc.)?

Question 1.4: How to ensure reliable performance of new materials during the lifetime of transformer?

Question 1.5: What is operational experience with refurbished transformers? What is expected lifetime compared to new units? How to justify refurbishing?

4 Preferential Subject 2 (PS2): Advances in transformer analytics

The subject covers:

- Data management: digitalisation and information model, online and offline test data, integration of condition and multiple data sources, data preparation for analytics
- Diagnostic and on-line monitoring: algorithm/guidelines for on-line monitoring, advanced interpretation of condition data, case studies
- Modelling: transformer digital twins (thermal, dielectric, mechanical, etc.), physics-based and hybrid models, failure probability and ageing models, applications of artificial intelligence

A total of 51 papers have been accepted for this preferential subject, which was the most of any preferential subject in Study Committee A2 and generated six discussion questions, each of which falls into one of the following subtopics:

- PS2-1: Diagnostics and on-line monitoring (19 papers)
- PS2-2: Modelling (13 papers)
- PS2-3: Applications of artificial intelligence (7 papers)
- PS2-4: Data management, assessment indices, and reliability aspects (12 papers)

4.1 PS2-1 Paper Summaries: Diagnostics and on-line monitoring

Paper 10158 (China) focuses on analysing vibration characteristics in converter transformers. The authors conduct simulation analyses and experimental studies, exploring the influence of factors like excitation voltage, load current, oil temperature, and harmonics on winding and core vibrations.

Paper 10317 (United States, Argentina, Italy) investigates the insulation properties of paper-liquid insulation models immersed in mineral oil and natural ester. The study includes Dielectric Frequency Response (DFR) tests, which evaluates the moisture content and insulating liquid conductivity, and Degree of Polymerisation (DP) analysis to assess thermal degradation. Over a 5-year non-accelerated aging period, the research highlights the superior cellulose preservation of natural esters compared to mineral oils.

Paper 10403 (United Kingdom, United States) analyses a large dataset of Dissolved Gas Analysis (DGA) records collected from over 700 transmission power transformers in the UK, spanning up to 63 years of service. The study employs statistical data analysis techniques to clean and process the data, revealing long-term DGA patterns that consider the service age of transformers. It also develops an automated technique to assess gas trends in transformers, aiding in asset management. The research identifies unique gas patterns and introduces an anomaly detection technique to prioritise monitoring for potential issues.

Paper 10612 (Poland) discusses the measurement uncertainty of online bushing monitoring systems. It highlights the importance of correcting network unbalance to improve the accuracy of tanδ and capacitance measurements. The study introduces a modification to the monitoring systems that allows for direct measurement of voltage vectors, synchronously sampled from voltage transformers and bushing test taps, and calculates corrected coefficients.

Paper 10663 (South Africa, United Kingdom) discusses moisture behaviour in transformers, showing how moisture levels vary with load and temperature. It examines the difficulties in positioning sensors and choosing the appropriate relative saturation alarm. Additionally, the study includes laboratory test results that compare sensor responses.

Paper 10888 (Norway, Sweden) discusses the need for accurate diagnostics to identify deteriorating bushings without the risks associated with invasive inspections. The case study presented in the publication illustrates how DFR helped identify a degraded bushing that required replacement, with subsequent investigations confirming the issue.

Paper 10890 (Norway, Switzerland, Slovenia, Austria, France) studies the dynamics of clamping pressure in power transformers. The research incorporates sensors between the clamping beam and the clamping ring for real-time monitoring. Data from a 40 MVA power transformer equipped with these sensors shows seasonal and load-related variations in clamping pressure, which are closely correlated with winding temperature. Two predictive models are introduced to estimate clamping pressure in-service, thus, being able to implement needed actions to correct it, if necessary, before a failure.

Paper 10930 (Canada) discusses three real-life use-cases that highlight both the benefits and challenges of online DGA monitoring. It covers warranty coverage, anomalies and misses in monitoring, and real-time decision-making. These case studies shed light on the complexities and unintended consequences end-users should consider when implementing online DGA monitoring for transformer health assessment and maintenance planning.

Paper 10939 (Mexico) addresses the issue of moisture in power transformers' insulation systems and the challenges associated with traditional solid insulation drying processes. This paper introduces a methodology that leverages the Internet of Things (IoT) and data analytics to optimise the drying process and achieve low moisture levels. It describes an architecture and software design for monitoring the drying process, considering transformer-specific insulation design data and real-time measurement of temperature, pressure, and environmental conditions.

Paper 11034 (Germany) explores the development of statistical methods for evaluating tap-changers' vibroacoustic characteristics. The study presents long-term monitoring results and demonstrates how the vibroacoustic measurement method can confirm the stability of On-Load Tap-Changer (OLTC) operation over extended periods, considering environmental factors like temperature.

Paper 11056 (Republic of Korea) introduces a transformer partial discharge localisation system that employs Ultra-High Frequency (UHF) sensors to measure partial discharge signals and identify fault locations. The developed system leverages both the transformer's structural information and the sensors' positional details to infer and validate the source locations. Case studies conducted on oil-filled and gas-insulated transformers validate the system's ability to accurately estimate partial discharge source locations.

Paper 11153 (Austria, Germany) explores the use of vibration measurements on a transformer's tank surface to detect voltage harmonics or DC bias in the excitation voltage. The study was motivated by increased transformer noise during site acceptance tests compared to factory acceptance tests, potentially linked to excitation voltage irregularities. The findings indicate that this approach can be a fast diagnostic tool during on-site inspections to understand the root cause of increased transformer noise.

Paper 11240 (Japan) introduces a non-invasive monitoring system that utilises magnetic sensors to track load currents and accelerometers to detect structural deformations caused by aging or external factors. The effectiveness of these monitoring techniques was validated through experiments conducted on two transformers.

Paper 11245 (Japan) introduces a calculation method for estimating the thermal deterioration of thermally upgraded paper. It employs a thermal circuit model for temperature calculation based on factory acceptance test data, load, and ambient temperature. The average degree of polymerization of insulation paper is calculated from the winding temperature history. The method's effectiveness was demonstrated in previous applications, with errors less than 10% for most transformers.

Paper 11274 (India) introduces a simplified equivalent circuit for interpreting end-to-end short-circuit Frequency Response Analysis (FRA) measurements. By categorising FRA measurements into three regions, the study calculates short-circuit reactance values and compares them to factory testing measurements for transformers of different vector groups. Additionally, the paper proposes an alternative FRA connection method specifically for star-star connected transformers, enabling short-circuit reactance evaluation.

Paper 11290 (India) aims to study the ageing markers models for assessing the aging and condition of transformers and reactors. Around 180 paper samples were collected from failed transformers and reactors, and oil samples were analysed for furan and methanol content. The implementation of methanol analysis has addressed the inherent limitations associated with furan analysis, particularly the slow furan evolution during the initial years.

Paper 11579 (Malaysia) presents an initiative undertaken by a Malaysian Grid utility, as part of its grid digital transformation. The monitoring platform incorporates various intelligent digital models, including DGA analytics, temperature and cooling system, transformer through current, dynamic asset health assessment index, remaining life assessment, and ageing index. This system incorporates data from online monitoring sensors and offline maintenance records.

Paper 11585 (Sweden) emphasises that accurate measurements and comprehensive data are essential for precise transformer condition assessments. The authors draw from their extensive experience in evaluating transformers using various diagnostic methods, such as oil analysis, DGA, and FRA, to illustrate how errors and uncertainties can arise when crucial information is missing or misrepresented. Ultimately, the paper offers practical recommendations to enhance the reliability of transformer diagnostic results.

Paper 11792 (Indonesia) presents extensive experience with online monitoring for power transformers, particularly focusing on lessons learned and challenges faced during their implementation. The study systematically identifies and addresses persistent issues, including sensor damage, measurement validity and communication disruptions. Comprehensive methodologies are employed to map vulnerable components, assess existing infrastructure, and evaluate various measurement methods.

4.2 PS2-2 Paper Summaries: Transformer modelling

Paper 10318 (United States) presents a digital twin model that simulates the degradation process using chemistry, thermodynamics, and water diffusion equations. The model calculates degradation rates for discrete regions of solid insulation in the windings, considering water generation due to paper degradation, and different types of liquid insulation.

Paper 10410 (Portugal) explores simplifications and assumptions to make CFD-based tools more compatible with engineering demands regarding response time. The paper presents two main approaches for simplifying CFD simulations: dimension reduction from 3D to 2D and simplifying the details of winding components. The focus is on achieving faster but reliable results for heat transfer and fluid flow.

Paper 10411 (Portugal) presents temperature rise tests on a 15 MVA power transformer filled with natural ester, using fibre optic probes to monitor temperature, and ultrasonic flowmeters to monitor the liquid flow rate. Experimental and computational results were compared with model predictions to gain insights into hot-spot location variations during dynamic loading, contributing to the understanding of transformer aging and fluid behaviour under real-world conditions.

Paper 10691 (Sweden, Spain, India) focuses on transformer thermal modelling of forced cooling design, particularly in OD cooling modes where circumferential variations play a role. Three-dimensional CFD analysis with turbulence is computationally intensive, so the paper presents a reduced order model that efficiently estimates pressure drop. The approach is validated by factory testing with fibre optic sensors installed at different azimuthal positions around the same winding disc.

Paper 10706 (Brazil, United-States) introduces a novel mathematical model for continuous water distribution calculation inside transformers. Comparing results with traditional methods highlights the value of this comprehensive thermo-chemical approach for accurate and detailed analysis of transformer behaviour in renewable energy installations, emphasising its significance for optimising performance and reliability in this context.

Paper 10841 (Canada, Serbia) proposes a dynamic thermal modelling approach based on a detailed thermal-hydraulic network model. This concept aims to create a high-fidelity digital twin of transformers' thermal behaviour, offering a comprehensive understanding of physical aspects, material properties, geometry, and equipment characteristics.

Paper 10920 (Slovenia, United Kingdom, Austria, France, Uruguay, Canada, Serbia) discusses the work of CIGRE's Working Group A2.60, which suggests improvements to the IEC dynamic transformer thermal model. The working group's objectives include improving the loading guide in three areas: variable cooling stage, variable tap position, and modelling of viscous effects in various types of insulating liquids.

Paper 10993 (Serbia) analyses the propagation and location of UHF PD signals in power transformers. The results from various transformer models provide insights into signal characteristics and source localisation, contributing to more reliable PD diagnosis and improved transformer health assessment.

Paper 11027 (Germany) evaluates distribution transformers cooling under steady-state and dynamic loadings using thermal hydraulic modelling. Validation through heat run tests, computational fluid dynamics, and fibre optic sensors enhances the model's accuracy, contributing to improved cooling system design and performance optimisation in dynamic loading applications.

Paper 11174 (Austria, Ukraine) demonstrates the utility of direct current hysteresis measurements conducted on power transformer terminals for the parametrisation of the Jiles-Atherton hysteresis model within a transformer topology model. These models enable the investigation of low-frequency dynamic transformer behaviour, such as during dc or geomagnetically induced current bias.

Paper 11518 (Republic of Korea) addresses the growing demand for higher-capacity cast resin transformers in power-intensive sectors, such as data centres, and the associated challenges in evaluating load losses and winding temperature rise in these transformers. The use of sheet windings, which are more susceptible to leakage flux-induced eddy current losses, makes load loss evaluation increasingly complex as transformer capacity increases. The load losses and temperature rise simulation results are validated through the testing of a 20 MVA prototype transformer, demonstrating the accuracy and consistency of the proposed methodology for evaluating large-capacity cast resin transformers.

Paper 11675 (Croatia) discusses the challenges posed by overvoltages on power transformers, including those with high-frequency components. Modern power transformers can be equipped with transient recorders to measure voltages at the bushing measurement taps. Lightning overvoltages at transformer terminals can be correlated with data from lightning location systems. Proper wide-band transformer models are essential for accurate simulation in programs like EMTP. Comparing EMTP simulations with on-site measurements helps assess model accuracy in simulating lightning overvoltages transferred through transformers.

Paper 11865 (India, NGN) developed a hybrid model of the transformer, based on existing thermal models and a data driven system, to evaluate the insulation loss of life, remaining useful life and ageing factors. This information can be used to estimate and optimise the rating of the transformer in real time, which in turn can ensure the reliability of the system during emergencies or peak loading conditions.

4.3 PS2-3 Paper Summaries: Application of artificial intelligence

Paper 10488 (Sweden) discusses the application of AI and machine learning in the manufacturing process of power transformers. The authors explore the use of AI to improve quality control, specifically in the assembly of transformer windings. They use a system that captures images of the winding components and employs AI algorithms to identify and classify them, cross-referencing the results with provided blueprints to detect any deviations.

Paper 10842 (Canada, Switzerland, Sweden) introduces the application of Physics-Informed Neural Networks (PINN) to estimate the local heat loss distribution in power transformers. The methodology involves measuring temperature data from the tank wall, top oil, and current flow, and using this information as input for the PINN model. PINN simultaneously estimates the temperature and the underlying dynamics, such as the heat diffusion partial differential equation, to determine the local heat loss distribution in different components of the transformer.

Paper 11151 (Colombia) introduces a real-time AI-based system that leverages digital fault recorders and SCADA sequence of events data to analyse faults in power transformers, distinguishing between harmless inrush currents and actual short circuits, identifying faulty phases, and determining the affected winding.

Paper 11243 (Japan) presents a method for estimating incipient faults in oil-immersed transformers by utilising machine learning and time series data of DGA. The study initially develops fault detection criteria using Random Forest machine learning on a dataset containing DGA results from various transformers. The results demonstrate that the proposed method can estimate incipient faults earlier than traditional criteria.

Paper 11278 (India) discusses a reliability centered maintenance approach for power transformers and reactors, incorporating AI and machine learning algorithms. Leveraging a dataset of over 40 billion data points from more than 3600 EHV class transformers and shunt reactors, the study derives health scores and probability of failure scores using various condition monitoring tests and historical data. These scores are then correlated with a risk model, resulting in revised maintenance schedules with a 38% reduction in annual maintenance hours.

Paper 11292 (India) introduces an AI-driven objective analysis framework for FRA. The framework includes relationship analysis between signatures using distance algorithms and correlation techniques, providing insights into changes and anomalies. Machine learning, including advanced AI algorithms, is employed for objective interpretation and classification of transformer faults based on FRA signatures.

Paper 11467 (Bahrain, United Kingdom) focuses on assessing the health of power transformers and proposes an innovative methodology to enhance the asset health index evaluation through the integration of Fuzzy Logic principles. The proposed approach overcomes the limitations of conventional weight-based methodologies and provides a more nuanced and accurate determination of the health index, particularly relying on oil and electrical data.

4.4 PS2-4 Paper Summaries: Data management, assessment indices, and reliability aspects

Paper 10126 (France) discusses the condition and management of a fleet of large power transformers. The utility conducted a quantitative risk-based analysis to determine an optimal replacement age for each transformer, leading to a shift towards preventive replacement policies. Additionally, they plan to significantly increase on-site refurbishment operations, focusing on main sub-component replacements and introducing monitoring systems to extend the transformers' lifespans and enhance network sustainability.

Paper 10404 (United Kingdom) addresses the persistent issue of PCBs in legacy electrical assets, which poses environmental and regulatory challenges due to their toxicity and the hard deadline of 31st

December 2025 for compliance with the Stockholm Convention provisions. Specifically, it focuses on pole-mounted transformers that lack sampling points for in-service testing, making it necessary to decommission and replace these units. The paper presents a statistical model that leverages industry data to assess the risk of PCB contamination.

Paper 10661 (South Africa) outlines the evolution of asset health condition assessment methods for power transformers in a major South African utility. The paper describes the challenges and stages in this process, from the original model to the development of an abbreviated methodology, and finally to the optimisation of the approach, which led to the removal of certain parameters based on their influence on the health score. The paper reflects on the lessons learned and the relationship between the asset health index and transformer failures.

Paper 11064 (Australia, Germany) discusses how utilities in Australia and New Zealand are using a probabilistic risk-based approach for maintaining and retiring power transformers. Due to the low probability of transformer failure, it is challenging for local utilities to gather sufficient failure data for statistical analysis. The paper highlights the importance of pooling data with the international community through CIGRE reliability surveys, which have collected extensive global transformer data since the mid-90s.

Paper 11187 (Colombia) introduces a predictive evaluation methodology for identifying failure risk patterns in bushings, emphasising the importance of early renewal to extend transformer life and reduce carbon emissions. As the lifespan of transformers exceeds the traditional 40-year reference, the paper emphasises the need for proactive evaluation and replacement strategies for bushings to maintain equipment reliability and mitigate risks.

Paper 11235 (Japan) investigates the aging and deterioration of shunt reactors. The study focuses on evaluating the remaining lifetime of these critical assets. DGA, the DP of insulation paper, and the clamping force of windings serve as condition assessment indicators. By comparing five dismantled shunt reactors from different manufacturers that have been in service for over 30 years, the paper confirms specific deterioration characteristics. Based on the investigation's results, the study concludes with replacement criteria for these critical components.

Paper 11427 (Germany) presents an approach for condition assessment of transformer fleet using maintenance information, including measurement data. Paper describes one real life example from a German power utility, how transformer fleet condition assessment can be done using two-dimensional methodology.

Paper 11432 (Germany) introduces the concept of Digital Twins as a novel approach to efficiently conduct collaborative condition assessments with third-party experts while maintaining data sovereignty at the TSO. The paper outlines a comprehensive approach based on the German Platform Industry 4.0 Asset Administration Shell concepts. It discusses different levels of transformer digital twins and their role in data exchange among stakeholders. It concludes by highlighting the potential to transform the power industry by improving various aspects, from manufacturing to maintenance, and simplifying remote access while enhancing safety.

Paper 11647 (Germany) discusses the challenges in assessing the condition of power transformers and the importance of forecasting their condition to plan maintenance and replacement measures effectively. Data on more than 3,500 transformers from 36 network operators in Germany, Switzerland, and Austria were collected to analyse the aging behaviour of power transformers. The authors explore the use of Markov chains to predict condition state changes, focusing on six physico-chemical oil properties.

Paper 11726 (Germany) explores various methods for assessing the health index of power transformers, highlighting advantages and disadvantages. Some existing methods mask the true rating, leading to inaccurate evaluations. To address this, the paper introduces a novel approach that maintains consistent weight spacing across conditions, ensuring a more precise determination of transformer health based on the health index value.

Paper 11742 (Indonesia) focuses on assessing the insulating systems of power transformers. It employs the recommendations outlined in CIGRE TB 761 to evaluate the dielectric condition of power transformers and calculates a single index to assess their state. The study compares the dielectric indices of 248 transformers, offering insights into their overall condition and relationships between various testing parameters and the transformers' operational age. Furthermore, the study explores the correlation between transformer age and the dielectric condition index.

Paper 11842 (Germany, Australia) discusses the work of CIGRE's Working Group A2.62, which continues collecting statistical data on transformer failures. The working group's objectives include examining changes in transformer reliability compared to previous surveys, assessing how new applications impact reliability, and creating hazard curves for failure and replacement for various transformer populations. To date, they have gathered operational data from more than four hundred thousand service years of transformers with voltages of at least 100 kV across twenty-seven countries.

4.5 4.5 Discussion and Questions for Preferential Subject No 2

Upon reviewing the papers, the following discussion points and questions emerged regarding Preferential Subject No. 2.

Discussion for PS2-1: Diagnostics and on-line monitoring

The central theme of these papers is the continuous improvement of transformer reliability and extended service life. Among the practical diagnostic methods, periodic DGA testing serves as the initial step for most utilities due to its historical effectiveness in diagnosing transformer conditions. Many utilities now combine continuous DGA monitoring with other systems, including moisture measurements, bushing monitoring, vibroacoustic measurement of OLTC, and UHF partial discharge monitoring. These experienced users share insights into online monitoring, emphasising lessons learned and challenges faced during implementation. Some utilities even integrate data from online monitoring sensors with offline maintenance records, creating intelligent digital models—the beginning of a digital twin.

Question 2.1: What are the key benefits of combining periodic testing and continuous monitoring systems in transformer maintenance and operation?

Question 2.2: How can users address challenges during the implementation of online monitoring and the creation of intelligent interpretation models for transformers?

Discussion for PS2-2: Modelling

Modelling transformers has always been essential for design, but there is a growing trend to use these models for predicting transformer behaviour during service. This shift has given rise to digital twin models (including thermal, dielectric, and mechanical aspects). The papers share experimental and computational findings, shedding light on transformer behaviour and ageing in real-world conditions. These insights underscore the ongoing need for model refinement. By leveraging this information, real-time optimisation of transformer maintenance and operation becomes possible, ensuring system reliability precisely when it matters most.

Question 2.3: How do digital twin models enhance users’ ability to predict transformer behaviour during actual service conditions, and what specific aspects (such as thermal, dielectric, or mechanical) should these models prioritise?

Discussion for PS2-3: Applications of artificial intelligence

AI and machine learning applications have transcended science fiction, proving their success in manufacturing processes and managing transformer fleets. Detecting faults during manufacturing or in service can significantly reduce maintenance outages and costs. Traditionally, maintenance strategies relied on time-based or condition-based approaches. However, advanced technologies and extensive datasets have introduced a new era of precision and efficiency in asset management. The papers explore and compare various AI techniques and machine learning algorithms, emphasising the need for users to create their own AI-driven frameworks. Many more tailored applications for specific diagnostic needs are expected in the years ahead.

Question 2.4: How do advanced technologies and extensive datasets enhance precision and efficiency in manufacturing and managing transformer assets through AI, machine learning and hybrid modelling? What challenges might users face when creating their own AI-driven frameworks for transformer diagnostics, and how can these challenges be addressed?

Discussion for PS2-4: Data management, assessment indices, and reliability aspects

All the papers converge on a common theme: asset management hinges on analytics, which rely on data. These papers emphasise the critical role of assets for energy utility companies and industrial operators, necessitating effective management to ensure high availability, extended lifespan, and cost-effective operations. CIGRE established working groups focused on transformer condition assessment, asset health indices, and reliability to address needs, providing valuable references. As a result, the industry has developed effective tools for asset management decisions, leveraging condition assessments and data uncertainty analysis.

Question 2.5: What data is essential for developing accurate assessment indices for power transformers? How is the data collected, processed, and validated to ensure accuracy?

5 Preferential Subject 3 (PS3): Reliability of transformers for renewable energy

The subject covers:

- Transformers for low carbon technologies: voltage < 100kV, wind and photovoltaic parks, battery energy storage and electric vehicle charger etc.
- Case studies and lessons learned: type of failure, root cause analysis, mode of operation. Recommendations concerning procurement, design, operation and asset management strategies.
- Failure Prevention: useful diagnostic methods and monitoring systems. Optimization of operating conditions and additional measures such as overvoltage protection, harmonic reduction, cooling optimisation etc.

A total of fourteen papers have been submitted to this preferential subject, categorized into the following sub-topics:

- PS3-1: Application and Case Study: Transformers for the integration of renewable energies (5 papers).
- PS3-2: Design and manufacturing: Proposals for resilient designs to withstand new stresses (6 papers).
- PS3-3: Life Cycle Considerations for power transformers to reduce environmental impact (3 papers).

5.1 PS3-1 Paper summaries: Application and Case Study: Transformers for the integration of renewable energies

Paper 10117 (Egypt) leverages transformer loading data in Egypt to investigate the impact of electric vehicle penetration. The investigation centres around a specific distribution transformer feeding 150 apartments and compares the expected transformer lifetime to the number of charging vehicles connected to the transformer. The authors also explore the impact on transformer life expectancy by varying two different transformer insulation system parameters in the model.

Paper 10646 (Argentina) presents case studies for two wind turbine transformer failures. The failures are evaluated against the original factory test results to determine if the root cause could have been detected during factory testing. The authors highlight the importance of leveraging recognized international transformer test standards as a potential method to improve wind turbine transformer reliability.

Paper 11063 (Australia) looks at the effect of rooftop photovoltaics on distribution transformer ageing. Transformers are categorised into four load profiles and the relative ageing of each is calculated. The study does not consider the effect of harmonics from PV systems. The results show that the transformer fleet in general is not prematurely aged due to PV penetration.

Paper 11286 (India) describes how energy efficiency, control of cooling and sharing of load could improve efficiency and avoid generation loss in solar plants. Different ratios of transformer no-load and load loss, and ratio of natural to forced cooling, are examined to determine the most efficient ratios. Control of the solar plant to provide maximum output in the event of loss of one transformer is also investigated.

Paper 11429 (Germany) describes five methods of determining the maximum rating of transformers with photovoltaic loading, using both static and dynamic models of hotspot temperature calculation. These models can then be used with various scenarios for the growth of photovoltaic installations, to determine when the transformer will reach its maximum capacity and will have to be replaced.

5.2 PS3-2 Paper summaries: Design and Manufacturing: Proposals for resilient designs withstanding new stresses

Paper 10544 (Spain) presents a method and device for protecting dry-type transformers from the effects of fast transient overvoltages. To validate this method, two dry-type windings were produced. One was equipped with protection equipment in the form of varistors, the other had no protection equipment. The tests performed and analysis of the results confirm the possibility of protection by installing several varistors connected to intermediate winding nodes, ensuring internal voltage levels under transient overvoltage conditions are limited.

Paper 11091 (Rep. of Korea) describes how a winding arrangement was chosen for a 5-winding transformer for renewable applications. It describes the process of selecting the winding arrangement (e.g. losses, impedance and short circuit withstand considerations) and compares test results to calculated values, and also suggests further work required to improve the calculations.

Paper 11120 (Turkey) is a study of design of electrostatic shields between HV and LV winding in transformers, which are used to reduce transfer of surge voltages between windings. The paper describes different material types and thicknesses, styles of shield and insulation materials used, calculating losses and thermal performance of the shields using finite element techniques. Results show that thin, separated aluminium shields give the best electrical and thermal performance.

Paper 11180 (Austria) describes benefits and drawbacks of using dry-type shunt reactors instead of oil-filled shunt reactors. The interfaces and civil works required for each are also examined. The conclusion is that, with higher voltage dry-type reactors now available, they may be more cost effective than oil-filled shunt reactors in many cases.

Paper 11316 (India) outlines aspects of design for wind turbine generator transformers that should be considered due to the unique application and load of this type of transformer. This includes losses, cooling, materials and construction.

Paper 11713 (Germany) describes control for a novel system for varying the voltage of a shunt reactor using fast-switching modules (FSM). Results from simulations show that the voltage control is improved over tap-change control without FSM. The paper does not cover the practical implementation of FSM with a tapped shunt reactor.

5.3 PS3-3 Paper summaries: Life Cycle Considerations for power transformers to reduce environmental impact

Paper 10498 (Portugal) uses an example to describe how the CO2 footprint and other environmental impacts of a transformer can be determined over the entire life cycle. Therefore the whole life cycle from the production of the raw materials to the recycling of the transformer at the end of life is involved. This article is based on the application of ISO 14040/44.

Paper 10413 (Portugal) introduces a new transformer concept (hybrid transformer) which is intended to help reduce the CO2 footprint over the service life of the transformer. Among other things, amorphous core material, power electronic controls and diagnostic systems are used for this purpose.

Paper 10707 (Brazil, United States, Switzerland, Spain) presents a comparison between different cooling methods of dry-type transformers used for renewable and enclosure type applications. The comparison focusses on sustainability and environmental factors by examining the CO2 footprint of different dry-type transformer cooling technologies. Dry-type transformers with the cooling types of natural air (AN), forced air (AF) and liquid cooled (CC) are included.

5.4 5.4 Discussion and Questions for PS3

Upon reviewing the papers, the following discussion points and questions emerged regarding Preferential Subject No. 3.

Discussion for PS3-1: Application and Case Study: Transformers for the integration of renewable energies

As most countries are now moving towards a low-carbon economy, renewable energy sources and electric power for heating and transport are becoming more prevalent. In the main, these sources and loads have to be integrated into existing electrical grids, which could have a detrimental effect on the existing infrastructure, including power and distribution transformers. In particular, these technologies are often integrated directly into distribution grids at lower voltages without any upgrade of the existing network.

Power transformers are essential for the integration of renewable energy sources and loads into electrical networks. These new applications bring with them particular stresses such as higher harmonics and varying loads but also new types of load such as charging of electric vehicles, which all place special demands on this equipment and can even lead to transformer failures. In these contributions, several different methods for assessing the maximum capacity, ageing and possible failure of transformers with these new energy sources and new loads were presented. In addition, experience was gained in operation, condition assessment and fault analysis. One important aspect that was raised is that transformers should be correctly specified, identifying the actual application for which they will be used and specifying the relevant standards. In many instances, this not the case and distribution transformers for conventional applications (step-down) have been purchased where these are not the correct type of transformer for the application.

The contributions look at different aspects of the transformer life, including load limitation under certain circumstances, effects of renewable energy loading on the existing grid and failure investigation correlated to the original test results.

Question 3.1: How do the stresses on transformers for renewable energies differ from those in conventional applications?

Question 3.2: What other positive or negative effect can embedded generation or renewable technologies have on transformers in the existing network?

Discussion for PS3-2: Design and Manufacturing: Proposals for resilient designs withstanding new stresses

New loads in the application of power transformers also require new design concepts. The papers in this section describe considerations on how the design of transformers and shunt reactors can be adapted to the new types of loads.

Several aspects of transformer and shunt reactor design are considered, looking at different applications, including wind turbine and solar farm transformers as well as shunt reactors used for voltage control in the network. These aspects include general design considerations for wind turbine applications, the effects of harmonics and fast transients, methods of connecting multiple devices (photovoltaic generators) into the grid, type of shunt reactor construction (dry or oil-filled) and shunt reactor voltage control. In addition to the use of different modifications to the internal structure, the use of power electronic components such as varistors is also discussed. Furthermore, the advantages and disadvantages of dry type vs. oil filled equipment are compared.

These contributions describe some novel and innovative design proposals as well as discussing established design approaches that could be improved or expanded. They open up possibilities for integration of different technologies into the traditional methods of designing and manufacturing transformers and shunt reactors.

Question 3.3: What other technologies or materials could be employed in the near future to enhance the design of transformers and reactors for renewable energy applications?

Discussion for PS3-3: Life Cycle Considerations for power transformers to reduce environmental impact

Transformers, like all manufactured items, have an environmental impact through use of raw materials, manufacturing energy costs, transport, energy losses (heat) during operation and recyclability at the end of life.

Reducing the CO2 footprint is our common goal to achieve a sustainable future and is a key factor in the design, manufacture, operation and recycling of transformers. The papers in the last part of this preferential subject discuss the CO2 footprint of transformers over the whole life cycle.

A method for determining the CO2 footprint of power transformers is presented, and suggestions made for future work to improve the environmental performance of transformers. New concepts, materials and methods are also discussed as possible means of reducing the environmental impact over the life of a transformer.

Question 3.4: What are the main impacts on the CO2 footprint of power transformers? What changes to transformer design, installation practices, operation or end-of-life strategies would be beneficial to reduce environmental impact and improve recyclability?