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CENTRE OF EXCELLENCE FOR TRANSFORMERS

FER

7th International Colloquium Transformer Research and Asset Management

Cavtat / Croatia,

May 06 - May 09, 2026

Editors: Bojan Trkulja,
Samir Keitoue, Žarko Janić,
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7th INTERNATIONAL COLLOQUIUM
Transformer Research and Asset Management

PROGRAMME

Cavtat, Croatia, May 06 - May 09, 2026

Hotel Croatia

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1. WORD OF WELCOME

Dear participants,

On behalf of the Organizing Committee, it is my great pleasure to welcome you to the 7th International Colloquium CIGRE SC A2 – "Transformer Research and Asset Management", taking place in Cavtat, Croatia, from May 6 to 9, 2026.

This Colloquium is proudly supported by the CIGRE National Committee of Croatia, the CIGRE Study Committee A2 – Transformers, as well as the Faculty of Electrical Engineering and Computing, University of Zagreb, and the Centre of Excellence for Transformers.

It is an honour to host this internationally recognized event, bringing together leading experts from across the globe to exchange knowledge, share best practices, challenge perspectives, validate different technical solutions, and strengthen professional and scientific collaboration between industry and academia.

Transformers remain a cornerstone of modern power systems – the backbone of a reliable and resilient energy infrastructure. At a time marked by rapid technological change, increased electrification, and the global transition toward sustainable energy systems, their importance is greater than ever.

This Colloquium provides a platform to address both established and emerging challenges, ranging from transformer life management, modelling and simulation, advanced materials, technologies and components to diagnostics and digitalization. Through technical sessions, tutorials, invited papers, and discussions, we aim to foster meaningful exchange and generate new insights that will shape the future of power engineering.

With a diverse international community of participants from more than twenty countries, this gathering offers not only an opportunity to share expertise, but also to inspire new ideas and build professional relationships that extend beyond the event itself. We encourage you to actively participate in all sessions and to engage in scientific and technical discussions in a friendly academic atmosphere.

We extend our sincere gratitude to all sponsors, exhibitors, paper authors, and members of the Technical Committee, whose dedication and support have made this event possible.

It is with great pleasure that we welcome you to Cavtat, and wish you a successful and inspiring Colloquium.

Yours sincerely,

Petar Bobek

Chairman of the Organizing Committee

2. TECHNICAL COMMITTEE

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Igor ŽIGER

4. PRESENTATIONS OF SPONSORS

Wednesday, May 06, 2026

6:00 p.m. - 7:30 p.m.	**Technology Sponsor event:** Get-together at MR stand: **100 years of Power behind Power**

Thursday, May 07, 2026

4:30 p.m. - 5.15 p.m.	Silver Sponsor panel discussion by Siemens Energy: **Stronger Together:** Building a Resilient and Sustainable Transformer Supply Chain Through Collaboration Moderated by: Stefanie Reuter
5:45 p.m. - 7:15 p.m.	**Bronze Sponsor Event:** Get-together at HAEFELY stand: **Transformer Networking Session with Selected Sparkling Wines**
7.15 p.m. - 8.00 p.m.	**Presentation of Golden Sponsor KONČAR - ELECTRICAL INDUSTRY Inc.**

5. MAIN TOPICS

Modelling and Simulation (M&S)

- Numerical modeling in design, multi-physics and coupled problems
- Transients, harmonics, lumped and distributed parameter models
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Materials, Components and New Technologies (MC&NT)

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Chairman: B. Trkulja

Thursday, May 07, 9:00 a.m. – 11:00 a.m.

1. (Invited Paper) Á. Portillo (Transformer Consultant, Uruguay)

DESIGN OF TRANSFORMERS FOR VERY FAST TRANSIENT OVERVOLTAGES

Increasingly, for different technical-economic reasons, gas-insulated substations (GIS) are being used in electrical systems instead of conventional air-insulated substations (AIS). The switching transients originating in GIS are called Very Fast Transient Overvoltages (VFTO) and are completely different from those originating in AIS, with different frequencies, amplitudes and waveforms. Conventional power transformers are designed to withstand the standard lightning and switching impulses (LI, LIC and SI according to IEC 60076-3). Modelling and behaviour of transformers for the frequency range of these tests (< 500 kHz) is well known, proved in the factory acceptance tests, and validated by successful operation in service. For VFTO, , however, no standard tests are available yet, therefore, the customer needs to define the VFTO test voltage that must be considered in the design of the transformer. The design of transformers that can withstand the effects of VFTO represents a great challenge and we will present in this work the state of the art of the dielectric design methodology including the selection of voltage wave shapes representative of VFTO, the transformer modelling requirements, the admissible electric field in insulating materials, the withstand of the different insulating structures and finally the proposed non-standard tests, when a transformer will be subjected to the effects of VFTO.

2. B. Gustavsen (SINTEF Energy Research, Trondheim, Norway)**, L. Oliveira** (Hitachi Energy, Brazil**, A. Portillo** (Transformer Consultant, Uruguay)**, F. Portillo** (Transformer Consultant, Uruguay)

EMPIRICAL REPRESENTATION OF TRANSFORMER BRANCH IMPEDANCE FREQUENCY DEPENDENCY

High-frequency transformer models for use in system transient studies should include the transformer's frequency dependent effects to give reliable simulation results. The most accurate white-box modeling approach is based on the branch impedance matrix Zb with inclusion of frequency-dependent effects, in combination with the capacitance matrix. The required calculation of Zb at many time frequency samples using FEM can be very time consuming, due to the large dimension of Z b. We show that the frequency dependency in Zb can be approximately taken into account by an empirical frequency response that is derived from an eigenvalue of Zb from a representative transformer. That way, the long computation time by FEM is avoided. The proposed method is demonstrated to be more accurate than usage of the classical Fergestad's damping factor method.

3. **M. Bauer** (Siemens Energy, Power Transformers Nuremberg, Germany)**,** **T. Wendlinger** (Siemens Energy, Power Transformers Linz, Austria)**, T. Manthe** (Siemens Energy, Power Transformers Nuremberg, Germany)**, J. Weisker** (Siemens Energy, Switchgear Berlin, Germany)**, M. Reuter** (Siemens Energy, Switchgear Berlin, Germany)

INTERACTION OF POWER TRANSFORMERS AND 145 KV GIS DISCONNECTORS: EXPERIMENTAL STUDY ON THE PROPAGATION OF VERY FAST TRANSIENT OVERVOLTAGES

Switching of gas-insulated disconnectors is particularly important in terms of very fast transient overvoltage (VFTO) phenomena [1]. This paper presents studies with an experimental setup that generates representative VFTOs with a 145 kV SF6-insulated GIS. The evaluation focuses on two different scenarios: The in-service operationally relevant switching of an unloaded bus section and second an induced internal fault to enclosure inside the GIS. For both scenarios, the GIS-disconnector is directly connected to a 20 MVA / 125,6 kV single-phase power transformer.

When it comes to VFTOs, an important question has to be answered from the perspective of the transformer design: How does the propagation of fast transient voltages behave and what interaction results with the power transformer? To be able to answer these questions practically in this study, steep transient surges are recorded at two relevant positions. First in front of the transformer oil-gas-bushing in the gas-insulated part of the system and in a second position inside the transformer tank at the high voltage leads close to the winding entrance. Here an optical electric field sensor allows the indirect detection of transient voltages without being subjected to any electro-magnetic interferences. The VFTO propagation and attenuation between these two positions can thus be quantified in the time domain. Based on high-resolution measurements it becomes evident that the observed VFTOs behave like combined overvoltages and need to be divided into very-fast-front-overvoltage (VFFO) and fast- front-overvoltage (FFO) signal components to ensure a clear characterization and parametrization. The results of both scenarios show steep initial VFFO components that are significantly attenuated in terms of amplitude and front time, due to damping effects along the wave propagation path from the GIS position in front of the transformer terminal and the area of the HV-winding entrance.

Generalized information about the parameters of VFTO behaviour in GIS systems, such as that provided by CIGRE WG 33/13-09 [2], are often used for transient analysis of power transformers. This publication, however, illustrates that no general assumptions about VFTO character can be made and underlines the necessity of taking the actual waveshapes on the transformer terminals into account. For very fast voltage components, it is clearly demonstrated that the damping behaviour caused by connections, transformer bushing, and winding leads cannot be neglected.

4. **F. Krpan** (Končar - Electrical Engineering Institute Ltd., Zagreb, Croatia)**,**
K. Petrović (Končar - Electrical Engineering Institute Ltd., Zagreb, Croatia)**,**
V. Kuprešanin (Končar - Electrical Engineering Institute Ltd., Zagreb, Croatia)**,**
P. Križić (Končar - Electrical Engineering Institute Ltd., Zagreb, Croatia)**,**
A. Marčina Brižić (Končar Power Transformers Ltd., Zagreb, Croatia)

OPTIMIZATION OF THE ELECTRICAL INSULATION BETWEEN GROUNDED ROD AND WINDING

In this paper, the optimization process of the clearance and the number of barriers between the grounded rod and the winding of the transformer is described. The minimum possible clearance is achieved by applying an appropriate number of barriers and with varying oil gap widths between them. This makes the optimization a two-parameter problem, requiring the identification of a suitable combination to meet the specified requirements regarding electrical insulation.

5. **M. Eslamian** (Hitachi Energy, Germany)**, E. Rahimpour** (Technical University of Applied Sciences Würzburg-Schweinfurt (THWS), Germany)**, K. Sethi** (Hitachi Energy, Germany)

AN INVESTIGATION ON THE EFFECT OF FREQUENCY DEPENDENT INDUCTANCE CALCULATION ON HIGH FREQUENCY MODELING OF TRANSFORMER WINDING

A common approach for analyzing transformer transients is to construct a detailed winding model composed of inductive and capacitive elements. Although equivalent circuits with constant inductances remain widely used in transient studies, extensive research shows that such models lack sufficient accuracy for predicting internal winding resonances which exhibit significant discrepancies in the time domain as well. To overcome this limitation, it is necessary to incorporate the frequency-dependent behavior of winding inductances, capturing proximity effects and eddy current losses within the conductors. A fully frequency-dependent model requires computing parameters over a broad frequency range and performing frequency-domain analysis, which is computationally demanding. In contrast, constant-inductance models remain attractive due to their mathematical simplicity and the availability of efficient, direct time-domain solution methods. These methods are especially advantageous when nonlinear components, such as zinc-oxide surge arresters, are incorporated internally. Considering these factors, this paper proposes a method to enhance constant-inductance models by selecting an appropriate inductance matrix computed at a higher frequency, thereby incorporating essential frequency-dependent effects. To this end, winding responses are evaluated using multiple inductance matrices derived at different computation frequencies, and it is shown that choosing the frequency based on the spectral content of the applied impulse waveform can noticeably improve the model accuracy. The proposed approach is validated through Frequency Response Analysis (FRA) and Recurrent Surge Oscillation (RSO) measurements performed on the active part of a 250-MVA power transformer. Measurements include both time- and frequency-domain voltage responses obtained from internal points of the high-voltage winding. This paper provides a comprehensive description of the method, including the construction of the equivalent model, parameter determination, and experimental verification.

6. **A. Fröhlich** (Graz University of Technology, Institute of Electrical Power Systems, Graz, Austria)**, D. Albert** (OMICRON electronics, Klaus, Austria)**, T. Bednarczyk** (OMICRON electronics, Klaus, Austria)**, S. Zirka** (Dnipro National University, Dnipro, Ukraine)**, G. Leber** (Siemens Energy Austria, Weiz, Austria)**, H. Renner** (Graz University of Technology, Institute of Electrical Power Systems, Graz, Austria)

ELECTROMAGNETIC MODELLING OF A PHASE-SHIFTING TRANSFORMER BASED ON DC HYSTERESIS MEASUREMENTS

This paper presents an electromagnetic model of a 600 MVA phase-shifting transformer using limited design data and DC hysteresis measurements. Saturation and hysteresis-based approaches are developed and validated against factory test results. In addition, the model is verified using a transformer model in RelaySimTest software, demonstrating its effectiveness for low-frequency transient analysis. The results show that DC hysteresis measurements allow effective parameterization, achieving good agreement with factory acceptance tests. The method enables accurate low-frequency transient modelling, even for in-service transformers.

7. **J. Raith** (Siemens Energy Austria GmbH, Weiz, Austria)**, P. Picher** (Hydro-Québec, Varennes, Canada)

THERMO-HYDRAULIC NETWORK MODELS: ACCURACY AND PERFORMANCE UNDER OPERATIONAL SCENARIOS

This paper presents a comparative analysis of simulation results from two thermo-hydraulic network models (THNMs) for transformers: one model in which the windings are represented on a disk-by-disk basis, and another in which each winding is modeled as a single aggregated hydraulic element. The study examines several time periods of field-collected operational data and compares simulation outputs with corresponding measurements. Particular attention is given to scenarios involving high loading, variations in cooling-system operation, and very low air ambient temperatures. Statistical analyses are performed to evaluate and demonstrate the accuracy of both models. Time intervals in which the simulations show significant deviations from the measurements are identified, and a potential method for improving THNM robustness under such disturbances is proposed. In the second part of the study, the models are used to determine both the steady-state winding hot- spot temperature and the transformer's dynamic loading capability under varying ambient conditions. These results are then compared to those obtained using the conventional IEC 60076-7 loading guide model. The findings provide valuable insights into the strengths and limitations of thermo-hydraulic modeling approaches and offer guidance for practical applications.

8. **D. Leljak** (Končar – Power Transformers. Ltd (Joint Venture of Siemens Energy and Končar), Zagreb, Croatia)**, P. Barišić** (Končar – Power Transformers. Ltd (Joint Venture of Siemens Energy and Končar), Zagreb, Croatia)

NUMERICAL ANALYSIS OF CLAMPING ELEMENT PRESSURE ON POWER TRANSFORMER CORE SHEETS

In this paper, numerical analysis is employed to calculate the pressure created by clamping elements on the power transformer core. Initially, the material behavior, obtained through experimental testing, was applied to a core section that incorporates all the observed clamping elements. Multiple finite element analyses were conducted to assess the influence of various clamping components, including bolts passing through the yoke, bandages, and crossbars, on the overall clamping system. Furthermore, the analyses were compared across different core types to identify variations in pressures on core sheets. Additionally, analyses were performed for multiple clamping frame thicknesses, providing insights into how it affects stress distribution.

9. **M. Gillet** (GE Vernova, France, Switzerland, India)**, B. Bošnjak** (GE Vernova, France, Switzerland, India)**, H. Landes** (InuTech GmbH, Germany)**, N. Kewat** (GE Vernova, France, Switzerland, India)

NUMERICAL VIBROACOUSTIC ANALYSIS OF A LARGE TRANSFORMER TANK INCLUDING STRUCTURAL AND NOISE OPTIMIZATION

This paper presents a coupled numerical vibroacoustic analysis of a 380 MVA power transformer intended for railway transport. The study employs finite element modelling of the transformer active part, oil, tank and surrounding air. Harmonic analysis at predetermined frequencies is performed to capture the complex coupled dynamic interactions between the transformer's structural components and acoustic fluid, namely insulating oil and air. The harmonic analysis uses a fully coupled approach between the structural and acoustic domain where the partial differential equations representing the vibroacoustic behaviour of the transformer are presented in a single matrix without the need to iteratively solve separate matrices for each physical domain. This approach yields a field solution that enables simple evaluation of the pressure distribution inside oil, tank vibrations and sound pressure radiated outside the tank. Some optimization solutions are introduced to prevent local resonance modes and to treat influence of air cavities.

Thursday, May 07, 11:15 a.m. – 12:45 p.m.

10. **E. Rahimpour** (Technical University of Applied Sciences Würzburg-Schweinfurt, Faculty of Electrical Engineering, Germany)**, A. Portillo** (Transformer Consultant, Uruguay)**, R. Castro Lopes** (EFACEC transformers, Portugal)

ANALYSING THE EFFECTS OF NON-STANDARD OVERVOLTAGES ON THE INTERNAL ELECTRICAL STRESSES ALONG THE TRANSFORMER WINDINGS

Transformer impulse testing is defined in detail in existing standards, for instance, IEC 60060-1 [1], IEC 60076-3 [2] and IEC 60076-4 [3]. The applied lightning impulse, the chopped wave impulse and switching impulse have been precisely characterized for testing power transformers. However, two subjects related to these testing are still challenges.

The first issue is that the impulse parameters can vary depending on testing schemes and transformer design. One typical matter therewith is influence of impulse parameters on electrical stresses inside the transformer winding and limitation of its permissible deviations. The second issue is that the measured real overvoltages in the power system differs from those defined in standards. Similarly to the first issue, the internals stresses along the windings will vary and might get higher values than the designed permissible electrical stresses.

Investigating the above-mentioned problems has been a part of the objectives of launching the CIGRE WG A2.63 “Transformer impulse testing”. The WG worked on the transformer impulse testing in three subgroups to study and analyse: A) High Frequency Power System Transients, B) Power Transformer Testing - Test Equipment and Techniques, and C) Transformer Transient Simulations and Dielectric Withstand of Transformer Insulation System. As a key action, the subgroups mentioned have been exchanging the results and discussing them together to make the study more effective and each of them will publish a Technical Brochure.

Another important objective of the WG A2.63 was verifying of the k-factor, which was introduced in the IEC 60060-1 and IEC 60076-3 to compensate for the overshoot at the front of the full wave lightning impulse. This approach was initially developed for the testing of dielectric materials, and, despite all its advantages, it is not applicable to complex transient phenomena in transformer windings. In general, the transient voltages in the oil ducts located far from winding terminals reach their maxima at times far beyond the impulse front and they are not affected by the overshoot [4]. Consequently, the application of k-factor needs to be reevaluated.

The effects of the mentioned issues on the minor insulation electrical stresses in the windings, i.e., the difficulties in generating standard waveshapes in the lab and the differently from the standard overvoltages appearing in power systems, have been studied intensively by subgroup (C) of the CIGRE WG A2.63. The investigation has considered and defined numerous different applied voltages instead of standard voltages. The study has additionally considered the effects of nonstandard overvoltages on different transformer designs including different types of windings.

Comparing by simulations the electrical stresses developed inside the windings due to the applied theoretical standard voltages with those due to real test voltages, and with those due to non-standard voltages appearing in operation, reveals the impacts of such variations, and shows that dielectric testing by standard voltages is not in all cases enough to avoid the failure risks in service. Consequently, new measures should be applied to avoid the failure risks due to real overvoltages appearing in operation.

11. **P. Jalal** (University of Zanjan, Electrical Engineering Department, Zanjan, Iran)**, H. R. Mirzaei** (University of Zanjan, Electrical Engineering Department, Zanjan, Iran)**, M. B. Ghorbal** (University of Zanjan, Electrical Engineering Department, Zanjan, Iran)**, E. Rahimpour** (Technical University of Applied Sciences Würzburg-Schweinfurt, Würzburg, Germany)

AN ACCURATE DETAILED MODEL FOR TRANSFORMER DISC WINDINGS SUITABLE FOR MEDIUM FREQUENCY RANGE

Accurate modeling of transformer windings is crucial for monitoring their condition and detecting potential faults. Traditional methods may sometimes not be accurate enough at high frequencies. To address this challenge, this study proposes a more detailed yet computationally efficient model that represents each turn of a disc winding using simple RLCM elements. Unlike the Multi-Transmission Line (MTL) model, which is complex and resource-intensive, the proposed model achieves reliable accuracy up to 2 MHz while significantly reducing modeling effort. To validate its performance, the frequency response (FR) of the test winding was measured using a conventional Sweep Frequency Response Analysis (SFRA) device. The results were compared with those obtained from simulations using a traditional detailed model, the MTL model, and a newly proposed detailed model. The comparison employed different evaluation criteria, including the Index of Frequency Deviation (IFD), Index of Amplitude Deviation (IAD), and Normalized Cross Correlation (NCC). The findings demonstrate close agreement between the measured and simulated FRs, confirming the accuracy and efficiency of the new model. The results demonstrate that the developed model provides a practical and effective framework for fault detection studies in real transformer windings, representing a crucial step toward reliable condition monitoring.

12. **W. Lee** (GE Vernova Power Transformers Technology, United Kingdom)**, G. Rajeev** (GE Vernova Power Transformers Technology, United Kingdom)**, T. Boroomand** (GE Vernova Power Transformers Technology, United Kingdom)**, G. Pattyson** (GE Vernova Power Transformers Technology, United Kingdom)

AI SOLUTIONS FOR TRANSFORMER TANK COVER OPTIMIZATION

Artificial Intelligence, historically, aims to reproduce human-like machine intelligence with human-like machine learning ability [1][2][3]. One fundamental approach is to follow or imitate human reasoning about the problem that is aimed to be addressed using machine learning techniques [4]. Machine learning has demonstrated its successful application to a wide range of problems. So far, the main such applications originate from large research labs, such as Deep Mind or Open AI. An important question is how to choose and develop an applications of machine learning methods in the context of mechanical design of power transformers. To address this, this paper proposes a CatBoost based framework. The novelty of this work lies in the integration of CatBoost to automate and refine traditional Design Handbook (DH) rule-based calculations, providing a 2.5% to 3.2% increase in prediction accuracy while achieving a 95% reduction in calculation time compared to DH rules methods.

13. **A. Al-Abadi** (Hitachi Energy Germany AG, Germany)**, W. Wu** (Hitachi Energy USA Inc., USA)**, I. Woyna** (Hitachi Energy Germany AG, Germany)

THERMAL NETWORK MODELING OF TRANSFORMER WINDINGS FOR ACCURATE HOTSPOT PREDICTION

The transformer hotspot is a critical region caused by complex non liner loss distribution with thermal-hydraulic coupling, which significantly affecting the efficiency, reliability and lifespan of the unit. Accurate identification of hotspots is crucial for the design, operation and maintenance of transformers. This paper proposes a network methodology for modelling the internal temperature distribution of a transformer winding, enabling the identification of hot spots. The methodology

discretizes the transformer into a network of interconnected nodes, each representing a specific conductor and its insulation. The thermal interactions between the nodes are modelled using a set of equations, accounting for heat transfer mechanisms such as conduction and convection. The resulting model can simulate the three-dimensional effect inside a transformer to capture the effect of the increase of the mean turn length from the inner to outer winding layers. To verify the accuracy of the proposed network modelling, its results are compared to those obtained from computational fluid dynamics (CFD) models and experimental tests. The validated model can be used to predict hotspot locations, optimize transformer design and develop more efficient cooling strategies, ultimately enhancing transformer performance and reliability. By providing an efficient and reliable tool for hot-spot identification, this research contributes towards the development of more resilient and efficient power systems.

14. **G. Bulatović** (Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Institute of Nuclear and Physical Engineering, Bratislava, Slovakia)**, P. Bokes** (Slovak University of Technology, Faculty of Electrical Engineering and Information Technology, Institute of Nuclear and Physical Engineering, Bratislava, Slovakia)**, J. Kurminský** (Technical University of Košice, Faculty of Electrical Engineering and Informatics, Košice, Slovakia)**, K. Paulovičová** (Institute of Experimental Physics SAS, Košice, Slovakia)**, M. Rajňák** (Institute of Experimental Physics SAS, Košice, Slovakia & Technical University of Košice, Faculty of Electrical Engineering and Informatics, Košice, Slovaki)

ANALYTICAL MODELING OF OIL CIRCULATION AND NANOPARTICLE IMPACT ON TRANSFORMER TEMPERATURE RISE

Analytical models of oil circulation and heat transfer provide a physically transparent and computationally efficient complement to numerical and experimental approaches for transformer thermal analysis. In this work, a vertically heated natural convection loop model for ONAN distribution transformers is employed to investigate the sensitivity of predicted oil temperatures to key hydraulic and thermophysical parameters: internal hydraulic resistance, effective heat transfer at the transformer top and finned surfaces, and oil viscosity variation motivated by nanoparticle-modified transformer oils. The results indicate that effective heat transfer from the finned surfaces is the dominant factor governing transformer temperature levels, while hydraulic resistance and top-surface heat transfer play secondary roles. Moderate viscosity variations are found to induce only weak changes in temperature distribution, despite their noticeable impact on circulation velocity.

15. **R. Sitar** (Hitachi Energy, Ludvika, Sweden)**, L. Chen** (Hitachi Energy, Ludvika, Sweden)**, M. Rydja** (KTH Royal Institute of Technology, Stockholm, Sweden)

DC BIAS CURRENTS IN HVDC TRANSFORMERS

Paper demonstrates a method of calculating flux distribution in core and its surroundings by means of circuit simulation. Circuits used in simulations are equivalent electrical circuits derived from the transformer magnetic circuit of core and its surroundings. Simulation presented are used to evaluate flux distribution in core for different designs of HVDC transformers. Influence of different DC bias current values on magnetization current and its harmonics are presented. Finally, a temperature rise model of the flitch plate coupled with the circuit simulation is presented. Such simulation process enables designers to quickly evaluate transformer thermal performance considering basic transformer electrical design data and events in the system such as DC bias currents.

16. **A. Gloc** (Končar – Distribution and Special Transformers Inc., Zagreb, Croatia)**,** **B. Jurišić** (Končar – Electrical Engineering Institute Inc., Zagreb, Croatia)**,** **B. Filipović-Grčić** (University of Zagreb Faculty of Electrical Engineering and Computing, Zagreb, Croatia)

GEOMAGNETICALLY INDUCED CURRENTS AND INFLUENCE ON POWER TRANSFORMER SATURATION

The paper studies geomagnetic disturbances and their impact on the electric power system. The resulting geomagnetically induced currents (GIC) have a very low frequency, in the range of 0.01 Hz to 0.5 Hz, and can therefore be considered quasi-direct current. The entry of direct current into a transformer can lead to its saturation, resulting in excessive heating, a significant increase in reactive power consumption, and the generation of even and odd harmonics. Increased reactive power consumption lowers the voltage in the network, while the produced harmonics interfere with the operation or can trigger unintended activation of relay protection systems or disconnection of reactive power compensators. Simulations were conducted using the EMTP software, in which a model of the IEEE 118-bus test system was developed. The impact of geomagnetic electric fields (GEF) of varying intensities and different angles of incidence relative to transmission lines was analyzed. The transformer connection group, protective measures, key results, and conclusions regarding the simulation of nonlinear and frequency-dependent models are also presented.

17. **H. Dodiya** (Senior R&D Engineer GLOMUS, Hitachi Energy, Maneja, India)**,** **I. Woyna** (R&D Principal Engineer Simulations GLOMUS, Hitachi Energy, Bad Honnef, Germany)**, L. De Mercato** (Global Technology Lead – GLOMUS, Hitachi Energy, Molinazzo di Monteggio, Switzerland)

ADVANCED SCALABLE WEBAPP APPROACH FOR AUTOMATED SIMULATION OF TRANSFORMER COMPONENTS USING PYTHON

Accelerating transformer development lifecycles through simulation automation requires the adoption of new technologies that reduce manual effort and democratize simulation workflows. Traditional approaches to simulation automation often involve multiple local software installations, require specialized skills, lack centralized version control, and do not offer unified database storage. To address these limitations, this paper presents a novel technology: a web-based application developed in a Python environment to enable streamlined access to simulation automation. Python's extensive ecosystem including AI, ML, NumPy, Pandas, and all PyAnsys modules facilitate seamless integration of current and future technologies within this interface. With this Pythonic web application, users can easily input data and visualize 3D simulation results across devices such as mobile phones, laptops, and workstations. The newly developed interface supports automation of complex non-linear Multiphysics simulation workflows, parameter input, in-browser 3D result visualization, and automatic report generation. This technology is applicable to any type of transformer or its components.

18. **D. Ruganec** (Končar – Power Transformers. Ltd., Joint Venture of Siemens Energy and Končar)**, P. Barišić** (Končar – Power Transformers. Ltd., Joint Venture of Siemens Energy and Končar, Zagreb, Croatia)

NUMERICAL MODELING AND DIRECT SOLVER DEVELOPMENT FOR CALCULATION OF POWER TRANSFORMER CORE CLAMPING SYSTEM ASSEMBLY

This paper presents a new numerical model for assessing the structural performance of a power transformer clamping system, focusing on two critical load cases: active part lifting (tanking) and short circuit. Numerical model levera ges Finite Element Analysis (FEA) approach in conjunction with a custom, in-house developed direct solver. The tool can be integrated early into the transformer design process. It outputs critical structural values, including component stresses,

bending moment distribution, and frame displacements. The model's predictions for rigidity and strength have been experimentally verified against manufactured transformer units and cross-compared with existing analytical and proprietary numerical calculation suite.

19. **B. Trkulja** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, T. Župan** (Siemens Energy, Zagreb, Croatia)**, Ž. Janić** (Siemens Energy, Zagreb, Croatia)**, A. Drandić** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)

ADAPTIVE CROSS APPROXIMATION FOR EFFICIENT MODELING OF FREQUENCY-DEPENDENT RESISTANCE IN MULTIPLE-CONDUCTOR SYSTEMS

This work introduces a numerical method for computing frequency-dependent resistance in multi-conductor systems, accounting for both skin- and proximity-effect. The results of our solver align with professional FEM software, outperforming analytical approaches at higher frequencies for axisymmetric geometries of planar coils and transformer windings. Computa- tional efficiency is enhanced by using Adaptive Cross Approximation (ACA) to reduce memory demands. This provides a fast and accurate technique essential for designing modern electromagnetic devices with densely packed conductors.

20. **S. Mikulić** (Končar - Distribution and Special Transformers Inc., Zagreb, Croatia)**, B. Okorn** (Končar - Distribution and Special Transformers Inc., Zagreb, Croatia)**, D. Žarko** (University of Zagreb Faculty of Electrical Engineering and Computing, Zagreb, Croatia)

CIRCULATING CURRENTS IN TRANSFORMER CLAMPING SYSTEM

The clamping system of a power transformer ensures the mechanical integrity of the active part during manufacturing, transport, normal operation, and short-circuit events. As it is exposed to stray magnetic fields, circulating currents develop within its closed structural configuration even under normal operating conditions, despite single-point earthing. These currents are associated with the energy of the winding leakage magnetic flux and the relative position of the clamping system within its spatial distribution. Consequently, their magnitude is greater in transformers with higher short- circuit voltage and at the plus tap position. Currents circulate in electrical loops in the lower and upper parts of the clamping system, where they are superimposed on conventional eddy currents, and may cause increased local losses, generation of fault gases, and thermal faults. The fundamental principles governing circulating currents were experimentally validated by measurements on two transformers during the manufacturing process.

21. **S. Frljić** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, A. Drandić** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, B. Trkulja** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)

THE INFLUENCE OF HYSTERESIS MODELING ON THE CALCULATION OF MAGNETIC FIELDS

Due to hysteresis effects, the magnetization curve of ferromagnetic material is a history-dependent, nonlinear relationship between the magnetic flux density B and the magnetic field H. Here, the H(t) waveform is calculated for a given B(t) excitation using the Preisach hysteresis model. The resulting hysteresis loop indicates the importance of more sophisticated modeling of ferromagnetic materials when the excitation deviates from a pure sine waveform and the material operates near saturation. A comparison with non-hysteretic approximations based on static magnetization curves highlights their tendency to underestimate waveform distortion and harmonic content.

22. **F. Vučić** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, Ž. Janić** (Siemens Energy, Zagreb, Croatia)**, B. Trkulja** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)

COMPUTATION OF THE TURN-BY-TURN INDUCTANCE MATRIX OF TRANSFORMER WINDINGS BY USING CYLINDRICAL MULTIPOLE EXPANSION

This paper presents an efficient analytical method for computing turn-by-turn inductance matrices of coaxial windings with circular geometry. Individual turns are modeled as very short thick coaxial coils of rectangular cross section with small thickness, and mutual inductances are evaluated using series-expansion techniques based on cylindrical multipole expansion. The method is implemented in C and validated against a reference numerical integration approach. Numerical results show excellent accuracy for most turn pairs and acceptable deviations for closely spaced turns, while achieving at least an order-of- magnitude reduction in computational time.

23. **M. Meuser** (Technical University of Applied Sciences Würzburg-Schweinfurt, Faculty of Electrical Engineering, Schweinfurt, Germany)**, E. Rahimpour** (Technical University of Applied Sciences Würzburg-Schweinfurt, Faculty of Electrical Engineering, Schweinfurt, Germany)**, M. Eslamian** (Hitachi Energy, Bad Honnef, Germany)

THE ABILITIES OF TDSF AND FDSF IN ANALYSING VOLTAGE DISTRIBUTION IN DIFFERENT TYPES OF DISC WINDINGS OF POWER TRANSFORMERS

Power transformers are required to be engineered to withstand overvoltages encountered throughout their operational lifespan. Typically, transformers are specified and assessed according to standard impulse waveshapes, such as the lightning impulse (1.2/50 μs), chopped lightning impulse, and switching impulse (250/2500 μs). Nonetheless, actual overvoltages within the power system may deviate from these standard test impulses. Consequently, it is essential to assess the severity of measured overvoltage waveshapes from the power system and their potential impact on transformer insulation. In the literature three established approaches for waveshape comparison exist: frequency domain severity factor (FDSF), time domain severity factor (TDSF), and the technique outlined in IEC 60071-2: 2023, Annex I. This study examines the effect of non-standard overvoltages on transformer insulation by employing two severity assessment methodologies: the Frequency Domain Severity Factor (FDSF) and the Time Domain Severity Factor (TDSF). Non-standard waveshapes are generated through systematic variation of parameters - such as front time, tail time, chopping time, fall time and undershoot - based on those defined in IEC 60076-3: 2018. This controlled methodology facilitates the isolation of individual waveform parameter influences on internal transient responses. The study applies these waveforms to detailed white-box single turn models of multiple transformer windings with disc ordinary, partially interleaved, fully interleaved and disc shielded arrangements. With the voltage distribution within the windings the severity of the generated non-standard waveforms is assessed in relation to the standard impulses. Consequently, the validity of the standard-defined waveforms for testing transformer winding insulation is evaluated. The results show that FDSF effectively highlights changes in spectral excitation introduced by fast fronts, short fall times, and large undershoots, whereas TDSF more directly captures localized dielectric stress along critical insulation paths within the winding. The study demonstrates that relying on a single severity metric can be misleading and that a combined FDSF and TDSF assessment provides a more robust basis for judging the insulation relevance of non-standard overvoltage waveforms.

24. **L. de Mercato** (Hitachi Energy Ltd., Switzerland), **S. Vannicola** (Hitachi Energy Ltd., Switzerland), **S. Ossola** (Hitachi Energy Ltd., Switzerland), **T. Nowak** (Hitachi Energy Research, Poland), **M. Osika** (Hitachi Energy Research, Poland)

NUMERICAL AND EXPERIMENTAL ANALYSIS OF RANDOM FATIGUE OF WELDED CONNECTIONS BASED ON THE DIRLIK METHOD

Welding is widely used in manufacturing for its efficiency and cost-effectiveness, but welded joints exhibit lower fatigue strength than base material, making weld seams critical under cyclic loading. Fatigue assessment methods include nominal stress, hot-spot, and effective notch approaches. Real structures often experience random loading, requiring frequency-domain fatigue analysis using statistical methods. This work proposes a Finite Element (FE)-based methodology to estimate fatigue life of welded components under stationary Gaussian random loading. The approach applies the hot-spot method for stress evaluation, uses maximum principal stress as the equivalent criterion, and employs the Dirlik method for cycle counting. Fatigue life is assessed using experimental S-N curves, as well as curves from Eurocode 3 and IIW standards. Experimental validation was performed on seven S355J2+N welded specimens subjected to random loading with known PSD. Measured fatigue lives showed good agreement with FE predictions, highlighting the method's conservatism. A comparative study using the effective notch method demonstrated improved accuracy. The proposed methodology offers a reliable tool for industrial fatigue assessment of welded structures under random loading.

25. **B. Peruničić** (Joint stock company “Elektromreza Srbije”, Belgrade, Serbia),
M. Marković (Joint stock company “Elektromreza Srbije”, Belgrade, Serbia),
G. Raletić (Joint stock company “Elektromreza Srbije”, Belgrade, Serbia),
N. Vučinić (Joint stock company “Elektromreza Srbije”, Belgrade, Serbia)

CHALLENGES REGARDING FACTORY ACCEPTANCE TEST OF LARGE UNIT OF VARIABLE SHUNT REACTOR

With the rapid integration of renewable energy sources in Serbia and across the wider Southeast European region, the need for expanding transmission infrastructure has become increasingly evident. This includes not only the reinforcement of national transmission systems but also the development of new cross-border interconnections aimed at enabling efficient energy exchange and facilitating the connection of large-scale projects that form the backbone of the ongoing energy transition. With the construction of new transmission infrastructure, voltage profiles across the system have increasingly deviated beyond acceptable operational limits. At the same time, the deregulation of the electricity market has shifted a significant portion of voltage control responsibility onto transmission system operators (TSOs). Consequently, maintaining stable voltage levels throughout the transmission grid has become a critical operational challenge, requiring the implementation of advanced reactive power compensation equipment such as large shunt reactors. The rating of such reactors can widely exceed the three- phase capacity of most reactor manufacturers' test facilities. International standards like IEC, IEEE and Cigre recommendation, allow some compromises in the testing of large shunt reactors, where testing with reduced power may be approved in agreement between customer and reactor manufacturer.

This paper discusses the challenges with testing of large shunt reactors, and how to verify that alternative test methods are reliable and accurate. It further describes how tests have been performed on large shunt reactors, and how to use the results to verify the quality and reliability, especially for power losses.

While alternative testing methods, such as single-phase testing or testing with reduced power, can be used when full three- phase testing is not possible due to limited test facility capacity, fully testing the shunt reactor with a three-phase energization and at full power remains the preferred and most accurate approach.

26. **Dj. Dukanac** (Joint Stock Company “Elektromreza Srbije” Belgrade, Serbia)

THE IMPACT OF NEW LIQUID DIELECTRIC IN POWER TRANSFORMER ON THE LOCATION AND DETECTION OF PARTIAL DISCHARGE USING UHF SENSORS

In this paper, to obtain more relevant information for partial discharge (PD) diagnosis and location in the case of two different liquid dielectrics (mineral oil (MO) and natural ester (NE)), simulations are conducted using two power transformer models equipped with models of four ultra-high frequency (UHF) sensors and a PD source created with the Ansys HFSS software. This paper investigates and explains the changes and differences in the first peaks (FPs), extreme amplitudes (EAs), initial delays, waveforms, weighted mean amplitudes, and weighted mean frequency shifts of UHF PD signals at four UHF sensors in the particular periods of 12.179 ns from the FPs and from the FPs until the ends of the signals’ records at 45 ns, because of their different propagation paths and attenuations in the power transformer; it also determines and explains the location of the PD source using the FP method in proposed cases of two different liquid dielectrics in the power transformer model. Also, the influences of reflected waves from the transformer’s metal parts on the signals at the UHF sensors are analysed. When comparing the NE model to the MO model, the FPs and EAs in the first wave packets of signals 1, 2, 3, and 4 at the corresponding sensors are, on average, 1.88 times and 1.28 times larger. The dipole antenna’s (serving as a source and sensors) radiated and accepted power curves’ peaks for MO and NE have a mutual frequency ratio of 1.198. The use of NE in the model clearly results in a greater inaccuracy for the PD source location of 1.017 mm.

27. **M. Teruvai** (Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India)**, S. V. Kulkarni** (Department of Electrical Engineering, Indian Institute of Technology Bombay, Mumbai, India)

ASSESSMENT OF TRANSFORMER INSULATION BY DECISION TREES USING A COMBINATIONAL WEIGHTING MODEL

Insulation monitoring of a transformer has evolved with advancements in assessing strategies focused on dissolved gases, oil, and paper attributes. Dielectric response measurements in the time domain provide important insights into the insulation condition. A comprehensive analysis of the outcomes from time-domain testing methods, including the recovery voltage method, polarization-depolarization current method, and extended Debye-equivalent circuit method, can reveal the accurate health state of insulation. The unification of multiple test measurements into a decision-making framework remains a challenge for coherent assessment, as each test attribute is associated with distinct physical phenomena. For this purpose, the authors aim to propose a hybrid multi-criteria decision-making-based algorithm. It consists of a combinational weighting model, which is developed to correlate nine measurements (eight different attributes from the three tests and 2-furaldehyde) with the necessary comparative correlations; 2-furaldehyde is considered because it directly indicates the health status of paper. The weighting model comprises both assigning subjective weights and deriving objective weights using the analytic hierarchy process and inter-criteria correlation method, respectively, to determine the relative importance of considered attributes. This integration reduces dependency on expert judgement or available data, thereby ensuring accurate decision- making. Furthermore, the weights are integrated with the attribute values to determine the quality index of insulation using a decision tree (DT) algorithm. It is a layered network which helps to classify the attribute values into different quarters of health conditions. The outcomes are compared with a similar kind of approach that utilizes a hybrid random forest-based improved TOPSIS method to manifest the superiority of the proposed weighting-based machine learning algorithm.

28. **A. Drandić** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, B. Trkulja** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, S. Frljić** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)

BOUNDARY ELEMENT AND OPTIMISATION-BASED METHODOLOGY FOR TRANSFORMER INSULATION DESIGN

This work presents a methodology for transformer insulation system design and optimisation. The approach integrates the boundary element method (BEM) for accurate electric field computation with a parameter-free metaheuristic optimisation algorithm to improve design. The optimisation procedure adjusts selected geometric insulation parameters to reduce peak electric field values while maintaining feasible design constraints. Numerical results demonstrate significant reductions in maximum electric field and material cost, with final electric field levels consistent with practical transformer operating ranges. The methodology provides a computationally efficient tool that can support practical transformer design processes where both accuracy and speed are required.

Chairman: Ž. Janić

Thursday, May 07, 2:15 p.m. – 4:15 p.m.

1. **(Invited Paper) C. Espedal** (SINTEF Energi, Department of Electric Power Technology, Trondheim, Norway)**, H. Bærug** (SINTEF Energi, Department of Electric Power Technology, Trondheim, Norway)**, H. Enoksen** (SINTEF Energi, Department of Electric Power Technology, Trondheim, Norway)**, D. Linhjell** (SINTEF Energi, Department of Electric Power Technology, Trondheim, Norway)**, L. E. Lundgaard** (SINTEF Energi, Department of Electric Power Technology, Trondheim, Norway)

THERMAL ASPECTS OF INSULATING LIQUIDS FOR TRANSFORMERS: OVERVIEW OF THE NEWLIFT PROJECT

The NewLifT (New Liquids for Transformers) project is a research initiative funded by the Norwegian Research Council and several industry partners, running from 2023 to 2027. In this paper, we summarise the project's objectives and current findings. The main objective of NewLifT is to establish new knowledge about the thermal properties of different insulating liquids, with a special focus on Arctic conditions. The project is divided into four parts. The first part investigates how differences in viscosities affect steady-state and transient thermal behavior in transformer windings at low temperatures. The second part studies moisture diffusion in paper/liquid systems under dynamic loads. The third part examines bubble formation in paper/liquid systems under temperature increase. Finally, the fourth part investigates the withstand voltages of liquids at low temperatures.

2. **M. Martinez** (Iberdrola Distribution i+DE, Madrid, Spain)**, J. Guimarães** (Faramax TRAFO SL, Cáceres, Spain)**, V. Radul** (Faramax TRAFO SL, Cáceres, Spain)**, M. Reigadas** (Faramax TRAFO SL, Cáceres, Spain)**, I. Gerasimova** (Faramax TRAFO SL, Cáceres, Spain)**, M. Picado** (Nynas AB, Stockholm, Sweden)**, H. Campelo** (Nynas AB, Stockholm, Sweden)

USE OF RE-REFINED OILS IN NEW TRANSFORMERS – PIONEERING PROJECT IN SPAIN

This work compiles the most up-to-date experience with the first ever power transformer immersed in a 100% re- refined transformer oil representing a significant milestone towards the Spanish grid carbon neutrality. This pioneering deployment demonstrates that the 100 % re-refined oil used performs equivalently to high-grade virgin naphthenic oils, with no deviations required in transformer design, factory testing or operational practices.

3. **V. Đurina** (Končar - Electrical Engineering Institute Ltd., Zagreb, Croatia)**, M. Schönberger** (Croatian Transmission System Operator Plc., Transmission area Osijek, Osijek, Croatia)**, V. Cindrić** (Končar - Electrical Engineering Institute Ltd., Zagreb, Croatia)

FORECASTING DISSOLVED GAS ANALYSIS IN POWER TRANSFORMERS USING MACHINE LEARNING APPROACHES

Dissolved gas analysis (DGA) is one of the most widely adopted techniques for monitoring the condition of power transformers. The interpretation of dissolved gases, such as hydrogen, methane, acetylene, ethylene, ethane, carbon monoxide and carbon dioxide provide insight into insulation degradation, developing faults, and potential failure mechanisms. Traditionally,

DGA has been applied as a diagnostic tool, with measured concentrations interpreted against standards or empirical thresholds. However, the increasing availability of historical DGA records from online monitoring systems and routine laboratory testing enables a transition from diagnosis toward prognostic analysis through time-series forecasting. Forecasting future gas concentrations offers the potential to support maintenance planning, risk-informed asset management, and early detection of abnormal trends. This paper evaluates multiple forecasting approaches with fundamentally different modelling assumptions, including linear regression, ARIMA, Long Short-Term Memory (LSTM) neural networks, and the Prophet model, using carbon monoxide and hydrogen concentrations as a case study. Model performance is assessed on both real transformer DGA data and a synthetically generated dataset designed to replicate underlying trends while introducing stronger seasonal variation. Comparative analysis demonstrates that while more complex models can provide visually detailed fits, simpler and more interpretable approaches often achieve equal or superior predictive accuracy for predominantly linear DGA trends, particularly for carbon monoxide. In contrast, hydrogen exhibits greater short-term variability, resulting in comparable performance across several models. The results highlight the importance of matching model complexity to gas- specific data characteristics and support the use of simple statistical models as effective tools for DGA-based assessment.

4. **L. Cantini** (Hitachi Energy, Monselice, Italy)**, G. Palermo** (Hitachi Energy, Monselice, Italy)**, P. Pavanello** (Hitachi Energy, Monselice, Italy)**, G. Bustreo** (Hitachi Energy, Monselice, Italy)

PAPER BULGING IN CONDUCTORS FOR POWER TRANSFORMER APPLICATION

Recent developments in modern technologies and the growing demand for environmental sustainability have influenced power transformers design. On one hand, manufacturers must reduce the amount of material used and therefore the transformer size; on the other hand, they must satisfy European regulations on energy efficiency [2]. Therefore, transformers operate closer to their limits. These new constraints lead to new design challenges. One of these issues is paper bulging in insulated conductors, which has been mentioned in the literature only briefly but can significantly affect the transformer windings and their cooling performance.

Short windings help reduce transformer height, but windings height depends on axial cooling ducts in disc or helical windings. Designers try to limit axial cooling ducts size to reduce the amount of active part copper and steel. However, the cooling ducts must allow to flow enough oil to cool the windings. Reducing the axial cooling ducts height can be risky, especially if the paper bulging has not been considered. The real cooling ducts height will be smaller because of the bulging. This bulging happens since the windings are compressed during production to improve their mechanical strength.

This paper investigates paper bulging in CTC, establishing correlation with the CTC parameters and manufacturing conditions, and develop a formulation to estimate the paper bulging itself. This value allows to know the amount of obstruction of the cooling duct caused by the paper bulging, and therefore the real height of the ducts used for cooling. A sever obstruction of the cooling ducts can lead to hot spot that can cause temperature rise test failure or accelerate transformer loss of life.

More than three hundred CTC samples from around 100 different CTC designs were analysed. Measurements on the paper insulation of the CTC under pressure were performed, emulating the winding production process. By exploiting these data, it was possible to obtain a formulation that reduces the uncertainty in estimating the paper bulging value. The aim is to give designers practical information that reduces the uncertainty in evaluating paper bulging and improves transformer cooling and reliability.

5. **S. Stagni** (Camlin Energy, Lisburn, Northern Ireland), **N. Jacob** (Camlin Energy, Lisburn, Northern Ireland), **D. Golovan** (Camlin Energy, Lisburn, Northern Ireland)

THERMAL FAULT IDENTIFICATION IN TRANSFORMER BUSHINGS USING ONLINE MONITORING AND OFFLINE TESTING

A 90 MVA, 230 kV:66 kV transformer exhibited abnormal bushing behavior detected through online monitoring , with dissipation factor trends suggesting a thermally driven fault . This triggered a detailed investigation involving offline electrical testing and oil analysis . Results confirmed significant deterioration , with dissipation factor values exceeding industry thresholds and dissolved gas concentrations indicating internal insulation degradation . Partial discharge data showed minimal activity , ruling out discharge -related defects . The affected bushing was classified as critically faulty and removed from service. Continued monitoring of remaining bushings is recommended , particularly during high-temperature operation. Broader surveillance of similar bushing types is advised to mitigate future risks.

6. **M. Rahmbeksch** (Enercon, Bremen, Germany), **J.-C. Duart** (DuPont, Meyrin, Switzerland), **R. Szewczyk** (DuPont, Warsaw, Poland)

REFERENCE TEMPERATURE CHALLENGES IN TRANSFORMERS WITH ALTERNATIVE INSULATION AND COOLING SYSTEMS

Over the years, wind-turbine step-up transformers have evolved significantly to meet the demands of renewable energy applications. The drive for compact designs and improved fire safety has led to a shift from conventional solid insulation and mineral oil toward alternative insulation systems and liquids such as silicone oil and synthetic ester, which also help extend transformer lifetime under high load conditions. Solid cellulose insulation has increasingly been replaced by thermally upgraded papers, aramid paper, and aramid pressboard, followed by the development of hybrid insulation systems that balance performance and thermal capability. At the same time, cooling technologies have progressed from natural -air cooling to forced-air and water-cooled systems, driven by rising turbine power ratings and space constraints. To support these developments, international standards and industry guides have been established to define insulation systems and permissible temperatures; however, differing definitions of winding reference temperature across standards continue to create challenges, particularly for efficiency and loss guarantees under regulations such as the European Ecodesign Directive. As new insulation and cooling practices emerge, reassessing reference-temperature definitions is essential to ensure accurate efficiency evaluation, regulatory compliance, and alignment with real operating conditions.

7. **L. Štrac** (Končar-Power Transformers Ltd., Zagreb, Croatia), **C. Toscano de Jesus** (Siemens Energy PT, Amadora, Portugal), **D. Fernandes Ribeiro** (Siemens Energy PT, Amadora, Portugal), **D. Fabac** (Končar-Power Transformers Ltd., Zagreb, Croatia)

USE OF MACHINE LEARNING TO CALCULATE THE COMPRESSED HEIGHT OF POWER TRANSFORMERS WINDINGS

This paper presents a method for predicting winding height using machine learning algorithms. The method uses collected design and measurement data to train a machine learning model. Winding and conductor design data are paired with measured pressure and final winding height. The model predicts final winding heights based on various design parameters. The methodology integrates advanced feature engineering, creating domain-specific features capturing geometric relationships, material properties, and manufacturing process parameters.

8. **A. Grđan** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, I. Žiger** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, Z. Hanić** (University of Zagreb Faculty of Electrical Engineering and Computing, Zagreb, Croatia)

CLOSED-FORM ANALYTICAL INDUCTIVE TRANSFORMER MODEL FOR ELECTROMAGNETIC TRANSIENT RESPONSE DURING LINE DISCHARGE

During a capacitive line or cable discharge, if an inductive voltage transformer is connected to the grid, most of the discharge current will pass through it. This is due to the fact that the high value of current quickly saturates the transformer, which then provides little impedance to the current. Although this characteristic becomes useful in protecting other connected equipment, it is necessary to consider discharge parameters that could potentially damage the transformer itself. Furthermore, depending on the discharge parameters, this phenomenon can cause the most severe mechanical stress an instrument transformer experiences during its lifetime. For this reason, accurately determining discharge parameters is crucial both in the design stage and in grid analysis. This paper presents an analytical model for fast, accurate determination of capacitive discharge parameters, thereby providing a complete description of all electrical quantities during the discharge. Additionally, it has been shown that the form of these expressions varies depending on the value of the damping factor, which encompasses all relevant discharge parameters.

9. **I. Žiger** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, M. Nenadić** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, A. Grđan** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, K. Koprivec** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, T. Župan** (Siemens Energy, Zagreb, Croatia)

REPEATED FLASHOVER TEST: INFLUENCING PARAMETER ANALYSIS

High-voltage equipment operates in more demanding conditions than was traditionally expected. Renewable energy sources, electric vehicles, capacitor banks and reactors are some of the contributing factors to an increased number of switching and disconnect operations high-voltage equipment is exposed to. Currently, there is no adequate standardized test that could realistically verify the behavior of instrument transformers under the increased number of switching operations.

For those reasons, the available literature suggests Repeated Flashover Test as a more representative alternative. The main objective of this paper is to present further findings on this topic. Specifically, the idea is to analyze two main influencing parameters on the transient magnitude: the applied voltage and disconnector operation speed. This data is crucial to determine an acceptable and realistic test sequence that is repeatable in different laboratories.

The research is performed as a part of a broader test cycle on a novel product type, the Combined Power Voltage Transformer (CPVT). The prototype unit is rated at 123 kV and 50 kVA. This paper will provide a summary of research performed thus far, detailed description of the test setup and recording system for very fast transients. Test data will include the measurement of the applied voltage profile, magnitude and number of transients, as well as the parameters of the test object, including dielectric insulation parameters (C and tgδ), partial discharge performance and chemical parameters of the insulation oil (gas rises and DGA).

With that the main aim is to provide additional guidance on the best practice for execution of a novel test that has been clearly demonstrated in previous literature as a valuable test for qualification of insulation systems of high voltage equipment operating in adverse conditions imposed by modern grid topologies and connected sources and devices.

Thursday, May 07, 5:15 p.m. – 5:45 p.m.

10. **M. Yoshida** (Chubu Electric Power Company, Inc., Nagoya, Japan)**, H. Isaji** (Chubu Electric Power Grid Company, Inc., Nagoya, Japan)

CONSIDERATIONS ON TRANSFORMER LIFE DETERMINED BY DETERIORATION OF INSULATING STRUCTURE MATERIALS

In order to verify the failure behavior of transformers due to deterioration, we conducted short-circuit tests on core-type disc winding transformers (3 types of winding layouts) with an average DP of 200 to 450, which is the life level of insulating paper. The results revealed that transformer failures caused by damage to the insulating paper do not occur, but instead there are transformers that fail due to electromagnetic mechanical forces acting in the axial direction of the transformer windings (external thrust, axial compressive force). Although the life of a transformer is generally considered to depend on the deterioration of the insulation paper, the mechanical strength of the insulating structure material played a role in the life of the transformer for some of the transformers of the core-type, disk-winding layout.

11. **I. Žiger** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, M. Nenadić** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, N. Budimir** (Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, D. Brezak** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)

VOLTAGE TRANSFORMER ACCURACY PERFORMANCE CALCULATION METHODS

The defining feature of any instrument transformer is its accuracy performance. The accuracy limits and associated burdens were introduced into international standards decades ago. In the meantime, measurement and protective devices have evolved significantly, meaning that the existing accuracy and burden definitions do not necessarily correspond to the needs of the modern market.

The aim of this paper is to showcase a calculation method, which is present in the upcoming IEC and IEEE instrument transformer drafts, as one of the aspects how to update the existing accuracy performance definitions and requirements. The proposed method should be used in conjunction with measured results obtained through routine or type accuracy tests. Its purpose is to provide accurate assessment of accuracy performance at different burdens and power factors than those the unit was tested at. In this paper the method will be validated on both inductive and capacitor voltage transformers with a thorough accuracy assessment performed for both transformer types.

Apart from describing and validating the method, the aim of the paper is to provide the best practice on how to use it effectively and what its limitations are. The intention that this paper can provide a broader context to the existing text in international standard drafts which could help make the use of the proposed method more widespread and accessible.

12. **M. Nenadić** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, I. Žiger** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, I. Crnković** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, D. Brezak** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)

INTERNAL FAULT TESTING AT THE VOLTAGE PART OF A COMBINED POWER VOLTAGE TRANSFORMER

The Combined Power Voltage Transformer (CPVT) - a novel product category in the field of instrument transformers has already been introduced conceptually, along with its benefits and applications. For all high-voltage apparatus, including instrument transformers, a design resistant to internal faults is crucial to prevent damage to nearby high-value equipment (power transformers, circuit breakers, etc.) and to ensure operational safety in the grid. Since the CPVT represents a new product category, its performance must be validated before being deployed in the grid on a larger scale. This paper provides insight into the CPVT's behavior under an internal fault in the voltage section. Results from numerical calculations, laboratory measurements, and experimental testing are presented. Since similar open-core designs have undergone internal-fault evaluations previously, key quantities of related transformer types are compared and analyzed within this paper.

13. **Z. Radaković** (University of Belgrade, School of Electrical Engineering, Belgrade, Serbia)**, M. Novković** (University of Belgrade, School of Electrical Engineering, Belgrade, Serbia)**, Á. Portillo** (Transformer Consultant, Uruguay)**, A. Pacheco Gomes** (WEG Equipamentos Elétricos S.A - Transmissão & Distribuição, Brazil)**, S. Guedes Montenegro** (CHESF, Brazil)

EXPLORING INTERMEDIATE RESULTS OF DYNAMIC THERMAL- HYDRAULIC NETWORK MODEL INFLUENCING CHARACTERISTIC TEMPERATURES INSIDE LIQUID IMMERSED TRANSFORMERS

The paper considers the detailed dynamic thermal-hydraulic network model DDTHNM, which is firmly grounded in physical principles, incorporating detailed construction data, material properties, and characteristics of the cooling equipment. It functions as a thermal digital twin of the transformer, delivering in-depth insights into local hydraulic and thermal processes under varying operational conditions – including changes in cooling stage, load, ambient temperature, tap position, and more.

In our previous papers, the theoretical foundations of two-dimensional models – accounting for both axial and radial directions – of hydraulic and thermal phenomena within power transformers are presented. Previous papers presented the results of its application and comparison with measurements for cold start and operation at low ambient temperatures.

In this paper we present the first application of DDTHNM to: a) double zig-zag winding, and b) radiator banks, connected to the tank through a system of external piping. . The paper describes the models for these constructions and demonstrates the application of DDTHNM in the design review phase. Once the transformer is manufactured, a follow-up publication will present the comparison of calculated values with measurements from the heat run test and, hopefully, from real transformer operation.

14. **S. Kroták** (Starkstrom Gerätebau GmbH, Cast Resin Transformer, Regensburg, Germany)**, D. Kress** (Starkstrom Gerätebau GmbH, Cast Resin Transformer, Regensburg, Germany)**, M. Svoboda** (Business Unit Dry SGB-SMIT GmbH, Regensburg, Germany)**, J. Hlaváč** (University of West Bohemia in Pilsen, Faculty of Mechanical Engineering, Department of Machine Design, Pilsen, Czechia)

SEISMIC STABILITY OF THE TECHNICAL SYSTEM CAST RESIN TRANSFORMER

Transformers are essential components of electrical power systems and enable the transmission and distribution of electricity across different voltage levels. They secure the operation of critical infrastructure such as hospitals, transport networks and industrial plants. In the context of escalating demands for reliable and accessible energy supplies, it is vital to protect this infrastructure from natural disasters like earthquakes. Damage to transformers can cause significant financial losses, power outages and disruptions to critical facilities. This study emphasizes the importance of ensuring sufficient earthquake resistance in cast resin transformers. These transformers are widely used due to their compact design and high resistance to environmental influences. The development and implementation of appropriate seismic design and robust construction is therefore of paramount importance in order to minimise risk of failure and damage. This study investigates measures to improve seismic qualification techniques for cast resin transformers. The goal is to increase the earthquake resilience of energy infrastructure. In regions characterised by high seismic activity, transformers must be designed with enhanced robustness to ensure a stable and secure power supply, like nuclear power plants. Special mounting and damping systems are necessary to withstand earthquakes, ensuring continuous operation and safety. It is essential that regular maintenance and testing for seismic resilience are carried out. Examples of disasters, such as the 2023 earthquake in Turkey and the 2001 earthquake in Gujarat, India, underscore the significance importance of robust transformers in seismic regions. These events highlight the necessity for the design and installation transformers capable of withstanding extreme conditions to ensure the safety and continuity of the power supply in critical infrastructures.

15. **D. Nath Jha** (Power Grid Corporation of India Limited, Gurgaon, India)**,**
P. Dr. Devaprasad (Power Grid Corporation of India Limited, Gurgaon, India)**,**
G. Agrawal (Power Grid Corporation of India Limited, Gurgaon, India)**,**
N. Srivastava (Power Grid Corporation of India Limited, Gurgaon, India)

SMARTER TRANSFORMERS, STRONGER GRID: POWERGRID'S DIGITAL CONDITION MONITORING JOURNEY

POWERGRID operates one of the world's largest EHV transformers and reactor fleets, where rapid network expansion has necessitated a transition from conventional maintenance practices to a digital, analytics-driven asset management model. This paper presents an integrated enterprise architecture encompassing business process digitization (including DREAMS and SAP-integrated charging clearances), field-level sensing (fiber-optic winding temperature monitoring, online DGA, and moisture management systems), centralized observability through a national monitoring centre (NTAMC), and analytics-enabled decision frameworks such as health indexing, Reliability-Centred Maintenance (RCM), and Dynamic Transformer Rating (DTR). At fleet scale, the approach enables standardized data capture and governance, implementation of risk-based maintenance using a biaxial probability–impact model, and seamless integration of automated workflows within ERP systems. Demonstrated outcomes include significant reduction in pre-commissioning clearance timelines (>40%), improved diagnostic consistency, reduction in planned and forced outages, and enhanced asset availability.

The paper further outlines a roadmap incorporating IoT-enabled thermography, homologous digital twins, and fleet-wide DTR deployment to strengthen reliability, asset utilization, and climate resilience of the transmission network.

16. **N. Kumar** (POWER GRID CORPORATION OF INDIA LIMITED, Rajasthan, India), **S. Behara** (POWER GRID CORPORATION OF INDIA LIMITED, Jeypore, Odisha, India)

ENHANCEMENT OF TAN-DELTA VALUES OF RESIN IMPREGNATED PAPER (RIP) TRANSFORMER BUSHINGS BY VARIOUS TECHNIQUES – CASE STUDY

This paper presents various methodologies for on-site improvement of Tan-delta (Tand) values of EHV resin- impregnated paper (RIP) Transformer bushing. The higher values of the tan delta indicate the failure of the bushing insulation, and it is not advisable to use it at the time of commissioning or during the operation. The bottom part of the RIP bushing is more sensitive to moisture. The improper housing of the bottom part of the RIP bushing results in increased moisture ingress into the bushing, leading to abnormalities in the Tan-delta values of the bushing. An increase in the Tan- delta values will prolong the project in terms of the period and the cost of rectification by the manufacturer/replacement with new RIP bushing. This paper details a practical case where improper storage of the RIP bushing leads to an increase in Tan- delta values of the bushing before the commissioning of a new transformer. The paper describes various approaches towards enhancing the Tan-delta values of the RIP bushing into the operational criteria, which economises the prolonging and cost of the project. The paper includes Tan-delta results of the pre- and post-application of the RIP bushing methodologies, which authenticate the applied practices.

17. **S. Behara** (POWER GRID CORPORATION OF INDIA LIMITED, Jeypore, Odisha, India), **N. Kumar** (POWER GRID CORPORATION OF INDIA LIMITED, Rajasthan, India)

ARRESTING OF OIL LEAKAGE IN DIFFERENT LOCATIONS OF TRANSFORMERS/ REACTOR USING THRIFTY TECHNIQUES - CASE STUDY

This paper presents new cost-effective techniques for arresting oil leakage in different locations of Transformers/reactors. The prime function of oil in the Transformer/reactor is to provide electrical insulation and coolant. Oil leakage is one of the crucial issues in the Transformer/reactor that happens during the service period for various reasons like design, quality, erection, ageing, etc. The oil leakage causes the intrusion of moisture and air into the transformer/reactor, which perverts the characteristics of the oil and paper insulation of the transformer/reactor. The paper details such instances where oil leaks from the different locations of the Transformer/reactor and an economical approach applied to arresting the oil leakage. The paper contains the procedure for the new techniques used for ceasing the oil leakage, along with pictures and a cost comparison.

Chairman: S. Keitoue

Friday, May 08, 9:00 a.m. – 11:00 a.m.

1. **(Invited Paper) S. Tenbohlen** (Institute of Power Transmission and High Voltage Technology (IEH), University of Stuttgart, Stuttgart, Germany)**, M. Siegel** (BSS Hochspannungstechnik GmbH, Sindelfingen, Germany)

CONDITION ASSESSMENT OF POWER TRANSFORMERS BASED ON UHF PD MEASUREMENT

Partial Discharge (PD) monitoring is a crucial diagnostic method for ensuring the reliability of power transformers and preventing unexpected failures. Measuring electromagnetic emissions in the ultra-high frequency (UHF: 300 MHz – 3 GHz) range offers distinct advantages over traditional charge-based methods, primarily due to its high sensitivity and strong resilience against external interference, such as corona discharges. This paper presents a comprehensive multi- sensor UHF PD monitoring system and details the application of two primary UHF PD sensor types: drain valve sensors for retrofitting existing units and window-type sensors for new transformers. To demonstrate the practical effectiveness of continuous UHF PD monitoring, two distinct case studies are discussed. A major focus is placed on an onsite investigation of wind turbine transformers that experienced unexplained trips and highly elevated hydrogen and methane concentrations. By utilizing continuous UHF PD monitoring alongside dissolved gas analysis (DGA), the study successfully correlates PD magnitude with temperature, pressure, and load variations within a synthetic ester insulation system. The findings reveal that thermally driven gas dynamics and supersaturation trigger intermittent, void-related PD, a diagnostic conclusion that was ultimately validated by forensic analysis.

2. **A. Padmanaban** (SERGI, France)**, M. Elkarii** (SERGI, France)**, D. Hamoir** (Transformer Protector Corp, USA)

FULL SCALE INTERNAL ARCING TEST IN 60 MVA POWER TRANSFORMER: TEST RESULTS ANALYSIS AND SIMULATION

Internal arcing in oil-filled transformers occurs when the insulating oil's dielectric strength breaks down, thereby generating a large gas bubble that rapidly expands in the surrounding incompressible oil, producing a shock wave. This expansion of the bubble generates high pressure, and if the pressure is not relieved quickly enough, the tank may rupture or explode. A rupture also exposes hot oil and combustible gases to air, creating a fire hazard. One strategy (among many others) is to equip transformers with Pressure Relief Devices (PRDs) to relieve this pressure. The paper describes full-scale internal arcing tests on an actual 60 MVA 115 kV-34.5 kV Y/19.918 kV power transformer at LAPEM in Irapuato, Mexico, in December 2022, to evaluate the effectiveness (dynamic performance) of two types of PRD: a non-resealable pressure relief device (NRPRD) and a conventional spring-operated pressure relief device (also referred to as a Pressure Relief Valve, PRV, in this paper). It details the experimental setup and instrumentation used to capture pressure, strain, and temperature data. Because direct measurements were only possible for some events, the paper also demonstrates how high-fidelity Computational Fluid Dynamics (CFD) simulations can be used to characterize pressure evolution inside the transformer during an internal arcing fault and to study the dynamic performance of PRDs under such loads. The transformer was intentionally subjected to six consecutive internal arcing faults, each lasting 100 milliseconds, with fault energies ranging from 0.6 MJ to 4 MJ, with no loss of structural integrity and while maintaining class II protection per IEC 61869-1:2023, implying no expulsion of projectiles due to rupture. Since there are no dedicated standards for internal arc

testing of power transformers, the electrical parameters used in the study were compared with IEC 61869-1:2023 for instrument transformers to gain insight. The tests were carried out with an asymmetrical factor of 2.55, exceeding the 1.7 value specified in that standard, noting that the standard limits the internal arc current to 60% of the short-time withstand current. Another important difference was the fault duration: IEC 61869-1:2023 calls for a single 0.3-second fault, whereas this campaign used six separate 0.1-second faults, reflecting the fact that power transformers are usually protected by systems that trip within about five cycles. The electrical parameters are also compared with IEEE C57.109 to gain additional insight. Overall, the campaign showed that the transformer remained structurally intact after all six internal arcing tests, despite conditions more severe than those specified for instrument transformers in IEC 61869-1:2023. The results further suggested that the NRPRD was the primary mechanism for mitigating overpressure, while the conventional spring-operated PRD (PRV) had a secondary effect, particularly when piping was included (noting that piping is essential for fire safety) and in the presence of highly transient pressure loading. The CFD simulation methods and results showed that such high-fidelity tools can be leveraged to optimize the PRDs (location, number, and size) specific to each transformer, probable fault location, and arc energy threshold, thereby improving transformer protection against internal arcing faults.

3. **Z. Jurković** (Končar – Distribution and Special Transformers Inc., Zagreb, Croatia)**, B. Trkulja** (University of Zagreb, Faculty of Electrical Engineering and Computing, Zagreb, Croatia)**, K. Petrović** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia)**, B. Jurišić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia)**, M. Jurković** (KONČAR – Distribution and Special Transformers Inc., Zagreb, Croatia)

EXPERIMENTAL EVALUATION OF MAGNETICALLY INDUCED LOSSES BASED ON TEMPERATURE MEASUREMENTS

This paper presents the second part of a study investigating stray losses in the outer core stacks of a power transformer. While the first part introduced a method for calculating these losses, this part focuses on experimentally evaluating them for validation purposes. Typically, magnetically induced losses are assessed by comparing total system losses with those in the excitation windings. However, the method presented here overcomes limitations of that approach, which relies on direct measurement of losses through the excitation winding's voltage and current. Instead, the proposed method compares the temperature rise from the evaluated loss with that from known losses. The experimental setup consists of a lamination stack, excitation windings, a U-shaped core, an electric heater for generating known losses, and thermal insulation. Thermal insulation minimizes the losses needed to reach the target temperature range and improves temperature distribution uniformity, facilitating accurate average temperature measurement. The experimentally determined magnetically induced losses serve as a benchmark for validating the loss calculations.

4. **A. Suleiman** (Network Management, AusNet, Melbourne, Australia & School of Information Technology and Electrical Engineering, The University of Queensland, St. Lucia, Australia)**, D. Susa** (GMB-TX, Melbourne, Australia)**, C. Ekanayake** (School of Information Technology and Electrical Engineering, The University of Queensland, St. Lucia, Australia)

FORMATION AND REMOVAL OF SILVER SULPHIDE ON OLTC CONTACTS: FIELD INVESTIGATIONS, PRACTICAL APPROACHES AND MAINTENANCE PERSPECTIVE

Silver sulphide (Ag_2S) formation on on-load tap changer (OLTC) selector switch contacts has emerged as a critical reliability concern for power transformers, particularly in units exposed to corrosive sulphur species such as elemental sulphur and dibenzyl disulfide (DBDS). This paper presents a comprehensive investigation into the mechanisms behind silver sulphide deposition, the influence of OLTC design factors on corrosion susceptibility, and the associated impacts on transformer electrical and dielectric performance. Drawing from recent field case studies, chemical reaction analysis, and diagnostic data, the study highlights how specific OLTC design elements—especially the extent of silver-coated components—substantially affect corrosion severity. Non-invasive diagnostic methods including DC winding resistance testing, dissolved gas analysis (DGA), and oil chemistry are evaluated for their effectiveness in early detection of contact degradation. A detailed cleaning and remediation procedure is proposed and validated through a real-world case study involving a 220/66/22 kV transformer exhibiting elevated DBDS levels and significant selector contact contamination. Results demonstrate that integrated mechanical cleaning, oil treatment, and improved preservation systems can restore OLTC performance. The findings emphasise the importance of corrosion-resistant design choices, proactive monitoring, and combined diagnostic approaches in mitigating the operational and economic risks associated with silver sulphide formation.

5. **M. Shaban** (National Grid Electricity Transmission, United Kingdom), **G. Wilson** (National Grid Electricity Transmission, United Kingdom), **R. Hooton** (National Grid Electricity Transmission, United Kingdom), **A. Lathan** (National Grid Electricity Transmission, United Kingdom), **K. Lennox** (Rawwater Applied Technology Ltd (RW), United Kingdom)

SPRAYED METAL FOR EFFECTING LEAKING TRANSFORMER REPAIRS (SMELTER)

With proper care transformers can provide reliable service well beyond their design life, but transformer oil leaks become more likely as equipment ages and create serious and expensive technical problems. There are many oils leak fixing techniques like welding, adhesives, brazing, and soldering for in time response to avoid abnormal operations. Designing leak proof methods is important to ensure a safe long-term transformer service. This paper investigates new technology for sealing leaking transformers for faster leak mitigation. A low melting point alloy, Molten Metal Manipulation (M3) was used in which molten alloy was sprayed directly against a flowing liquid leak to stop it. The spray proved to be successful on both leaking gaskets and dissimilar material flange leaks. The spray technology was integrated with a Robotic arm to detect the leak and spray at the target area only to reduce the residue and enhance the safety distance. Significant leak reduction was achieved with no surface preparation against dripping oil. Post-application pressure and temperature cycling supported proof of feasibility.

6. **D. Vrsaljko** (Končar - Electrical Engineering Institute, Zagreb, Croatia), **I. Radić** (Končar - Distribution and Special Transformers, Zagreb, Croatia), **V. Đurina** (Končar - Electrical Engineering Institute, Zagreb, Croatia), **I. Krivačić** (Končar - Distribution and Special Transformers, Zagreb, Croatia), **V. Haramija** (Končar - Electrical Engineering Institute, Zagreb, Croatia)

UNUSUAL X-WAX FORMATION IN DISTRIBUTION TRANSFORMER – CASE STUDY

This paper investigates an unusual white, wax-like contamination observed on the active part of a 630 kVA natural ester filled distribution transformer that failed prematurely in service. Factory tests upon transformer return to servicerevealed abnormal transformation ratio, asymmetrical resistance, and short-circuit impedance deviations, followed by the detection of a severe electrical fault on the high-voltage winding. After opening the unit, extensive solid deposits were found covering windings, insulation, and metallic components. Identification of such unknown solid ageing products is complex, time- consuming, and costly when the analytical direction is unclear. Targeted analyses using ATR-FTIR and DSC were performed and compared with relevant literature. The results indicate the presence of x-wax formed from natural ester insulating liquid, combined with a phenolic solid additive that likely acted as a crystallization nucleus. Due to extensive contamination and major electrical damage, the transformer was replaced.

7. **S. Selzer** (University of Wuppertal, Institute of Power Systems Engineering, Wuppertal, Germany)**, N. Bäcker** (University of Wuppertal, Institute of Power Systems Engineering, Wuppertal, Germany & Amprion GmbH, Dortmund, Germany)**, M. Zdrallek** (University of Wuppertal, Institute of Power Systems Engineering, Wuppertal, Germany)**, K. Maurer** (Maschinenfabrik Reinhausen GmbH, Regensburg, Germany)**, K. Lindl** (Maschinenfabrik Reinhausen GmbH, Regensburg, Germany)

NONLINEAR AGING BEHAVIOR OF POWER TRANSFORMERS UNDER INCREASING LOAD

The worldwide rise in electricity demand, driven by new types of loads, and an increasing share of variable renewable energy generation, presents significant challenges for power system operators. The reliable operation of power systems critically depends on the performance of power transformers, which play a central role in energy transmission. This paper investigates the influence of loading conditions on transformer aging. The statistical analysis shows that thermal stress is the dominant factor governing transformer aging. Moreover, the results indicate a pronounced temperature dependence of the aging curves, whose shape changes with temperature from an initially linear trend to a nonlinear, partially exponential progression. These findings highlight the need for more accurate determination of the load and temperature of power transformers to assess transformer lifetime and ensure grid reliability under future operating scenarios.

8. **I. Woyna** (Hitachi Energy AG, Germany)**, A. Al-Abadi** (Hitachi Energy AG, Germany)**, D. Parma** (Hitachi Energy India Limited, India)

ANALYSIS OF RESONANT CHARACTERISTICS OF TRANSFORMERS USING NATURAL FREQUENCIES

This paper presents a finite-element-based methodology for deriving frequency-dependent impedance matrices of transformer windings and for analysing their resonance behaviour in relation to different insulation systems. By comparing dry, mineral-oil-immersed, and retrofilled natural-ester insulation in a 630 kVA layer-wound HV winding, the study demonstrates how the dielectric properties of the insulation medium influence capacitive coupling, resonance damping, and internal voltage stress within an IEC-consistent Frequency Response Analysis (FRA) framework.

9. **P. Masmeier** (Messko GmbH, Oberursel, Germany)**, Dr. J. Kreling** (Messko GmbH, Oberursel, Germany)**, Dr. A. Kurz** (Messko GmbH, Oberursel, Germany)

NEW APPROACH FOR DIFFERENTIATED HEALTH INDEX FOR SUBSTATION ASSETS

Health indices, which are calculated to estimate the probability of asset failures in substations, are a valuable tool for both operators and asset managers. For the operator, they can display the current status of transformers, circuit breakers, cables, and other components, enabling quick decision-making, especially in response to alarms. For asset managers, health indices support the prioritization and planning of inspections, as well as the scheduling and allocation of maintenance efforts.

There are numerous ways to calculate a health index, but no established standard. Their calculation and interpretation must be defined carefully in order to draw the correct consequences. This paper presents an approach considering the possible failure modes potentially occurring on the different devices during their service life. It combines these with any measurable data, thus ensuring that not only the currently obtained parameters are included, but also all theoretically relevant

indicators for assessing the asset's condition. Such methodology, which can be considered as a generalized top-down approach, inherits deep knowledge of different substation assets. Every class of asset (e.g. power transformers, circuit breakers, etc.) is characterized by a comprehensive correlation table, that connects the mentioned failure modes with measurable parameters ("condition indicators").

Finally, the scoring is aggregated from the particular condition indicators. Moreover, a tolerance value is calculated, which represents the scoring's uncertainty from precision of measuring, outdating of data acquisition and data availability. Furthermore, it indicates possible root causes for the most probable occurred failure modes and gives hints on missing parameters.

Friday, May 08, 11:15 a.m. – 12:45 p.m.

10. **I. Radečić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **B. Jurišić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **I. Ivanović** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **V. Jerbić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **M. Perković** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **D. Filipovic-Grčić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **M. Schönberger** (HOPS Plc., Zagreb, Croatia)

SMART BUSHING SURVEILLANCE FOR A SAFER POWER GRID

Maintenance of electrical power equipment is progressively shifting from time-based practices to condition- based, reliability-centered strategies that depend strongly on the integration of real-time monitoring systems. Such monitoring solutions deliver essential insights into key components of transformers and reactors. Using this data, operators can evaluate equipment condition and make informed decisions on maintenance, thereby extending service life and improving reliability. Among transformer components, bushings represent one of the most vulnerable elements due to their role and location. They are subjected to high dielectric stresses, environmental effects, overvoltages from grid disturbances, and mechanical forces arising from connection weight, their own mass, ice and snow accumulation, and thermal expansion. Studies indicate that bushing contributes disproportionately to transformer failures, despite their relatively low cost compared to the potential consequences of failure. For this reason, their real-time monitoring is an essential aspect of reliable transformer operation, as well as of other equipment where they are integral, such as high-voltage reactors. This paper reviews the literature on real-time bushing monitoring and outlines the most commonly monitored parameters of bushing. Finally, the paper includes a brief analysis of an actual event from the Croatian transmission network. It presents a case where a monitoring system installed on a high-voltage reactor detected deviations in bushing parameters, enabling early fault identification before breakdown occurred. The presented case is based on the fast response of a real-time system with respect to the implementation of a reference method for monitoring bushings.

11. **I. Radečić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **V. Jerbić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **I. Ivanović** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **B. Jurišić** (Končar – Electrical Engineering Institute Ltd., Zagreb, Croatia), **M. Nenadić** (Končar – Instrument Transformers. Inc, Zagreb, Croatia), **I. Žiger** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)

REAL-TIME MONITORING OF STATION SERVICE VOLTAGE TRANSFORMER (SSVT)

Building on the principles of inductive voltage transformer design, the high-power voltage transformer, also known as station service voltage transformer (SSVT), is engineered to supply auxiliary power for substations and enable rural electrification. An SSVT is a high-power station service voltage transformer capable of taking power directly from the grid line and delivering it to secondary equipment. This smart solution is highly suitable for substations, island power supplies, and mobile variable power supply schemes. Since a power transformer represents a significantly higher investment, implementing a monitoring system to track its condition is considered a logical and well-justified decision. In the case of an SSVT, the situation is somewhat different, as its cost is several times lower compared to that of a conventional power transformer. For this reason, condition monitoring of SSVTs has often been regarded as uneconomical. However, with the advancement of modern technologies and the decreasing cost of real-time monitoring systems,

monitoring SSVTs is becoming increasingly feasible and can substantially enhance the overall reliability of the power grid. This paper presents the parameters that can be monitored on an SSVT. Additionally, the validation of transient measurements conducted in a high-voltage laboratory is presented, along with the validation of the setup for measuring neutral current, confirming the reliability of the proposed measurement system under test conditions.

12. **J. Ivankić** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, I. Žiger** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)**, D. Brezak** (Končar – Instrument Transformers. Inc, Zagreb, Croatia)

CHALLENGES IN TEMPERATURE RISE TESTING OF STATION SERVICE VOLTAGE TRANSFORMERS WITH MEDIUM-VOLTAGE SECONDARY WINDINGS

Station Service Voltage Transformers (SSVTs) are single-phase transformers used to supply auxiliary power for substations and, increasingly, for applications such as rural electrification, EV charging, and remote industrial loads. To support power transmission over longer distances from high-capacity transformers, SSVTs with medium-voltage secondary windings (typically ≥7.2 kV) are being introduced. While their dielectric characteristics have been previously studied, these designs introduce new challenges in testing, particularly for temperature rise tests. This paper considers a 145 kV, 50 kVA SSVT with a 7.2 kV nominal secondary winding voltage.

Typically, temperature rise tests of power transformers are performed using the short-circuit method. However, such methodology is typically inapplicable to SSVTs, which are commonly tested under load. That means that the burdens used for temperature rise testing need to be specifically designed. In this case, the burden design is specifically complex due to the rated voltage of the secondary winding. With that in mind, this paper focuses on the detailed test setup, burden configuration and other aspects needed to successfully complete a temperature rise tests of SSVTs with medium-voltage secondary windings.

13. **M. Bilal Ghorbal** (University of Zanjan, Electrical Engineering Department, Zanjan, Iran)**, H. Reza Mirzaei** (University of Zanjan, Electrical Engineering Department, Zanjan, Iran)**, E. Rahimpour** (Technical University of Applied Sciences Würzburg-Schweinfurt, Würzburg, Germany)

IDENTIFICATION OF ELECTRICAL FAULTS IN A TRANSFORMER WINDING USING UNSUPERVISED DIMENSIONALITY REDUCTION AND CLASSIFICATION ALGORITHMS

Transformer windings are usually exposed to various electrical stresses, such as the overvoltages generated in power grids. When overvoltage exceeds the winding insulation withstand level, various electrical failures can occur. For disc- type windings, overvoltages, depending on insulation condition and aging level, may lead to complete failure. Detecting the type of these failures using computerized methods can reduce the time and effort required to determine them in High-Voltage (HV) laboratories. Discriminating between electrical failures in the windings can be performed using various techniques. The Frequency Response Analysis (FRA) technique is commonly used for fault detection in transformer windings. In the present paper, the FRA technique is first used to measure the Transfer Function (TF) of a single HV disc winding under intact and faulty conditions with varying severities. Afterward, the measured TFs are arranged in a matrix and subjected to a Dimension Reduction Algorithm (DRA) to reduce their high dimensionality, extract the relevant features, and visualize them in a 2D space. Applying the DRA to the formed matrix yields two distinct clusters corresponding to disc-to-disc and turn-to- turn faults. Finally, two new unknown faults are selected as test data, and an unsupervised approach, such as k-means, is used to determine their types.

14. **E. Rahimpour** (Technical University of Applied Sciences Würzburg-Schweinfurt, Faculty of Electrical Engineering, Germany), **A. Portillo** (Transformer Consultant, Uruguay), **B. Jurišić** (Končar – Electrical Engineering Institute, Croatia)

NON-STANDARD, HIGH FREQUENCY POWER SYSTEM TRANSIENTS

A better understanding of the interaction between power transformers and reactors with the power system regarding high frequency transients is essential to improve equipment reliability in the presence of these types of transients. Operational experience has shown a substantial number of unexpected dielectric failures due to unknown causes that may be linked to this condition.

This paper strives to give an answer about which overvoltages can appear in the power system and how their waveshapes differ from the standard test impulses. Transformers and shunt reactors are dimensioned to withstand standard impulses but during their operational lifetime they face many different overvoltages. In general, overvoltages in the power system are caused by switching or lightning. Depending on the network topology as well as the nature of the event that triggered overvoltages, their waveshapes differ. Such overvoltages may cause transformer failure even though the transformer or shunt reactor is adequately protected by the surge arrester. Such an event is recognized as internal resonance appearing inside a transformer as a result of interaction between the system and the transformer itself. Moreover, repetitive impulses are recognized as another event which can lead to inner insulation failure. To adequately evaluate the overvoltages that may occur at transformer terminals, it is necessary to measure or simulate overvoltage.

Investigating the above-mentioned topic has been a part of the objectives of launching the CIGRE WG A2.63 “Transformer impulse testing”. The WG worked on the transformer impulse testing in three subgroups to study and analyze: A) High Frequency Power System Transients, B) Power Transformer Testing - Test Equipment and Techniques, and C) Transformer Transient Simulations and Dielectric Withstand of Transformer Insulation System. This paper summarizes investigations carried out under part A) High Frequency Power System Transients.

15. **I. Daminov** (Nantes University, Institut de Recherche en Énergie Électrique de Nantes Atlantique, Saint-Nazaire, France & IMT Atlantique, Department of Energy Systems and Environment, Nantes, France), **T. Gradnik** (Elektroinstitut Milan Vidmar, Ljubljana, Slovenia), **T. Laneryd** (Hitachi Energy Research, Västerås, Sweden)

DYNAMIC THERMAL RATING OF POWER TRANSFORMERS – CONCEPTS, STANDARDS, AND APPLICATIONS

Transformer loading capability has traditionally been expressed through fixed ratings but increasing operational demands and integration of intermittent renewable generation have intensified the need for more flexible and accurate approaches. Dynamic Thermal Ratings (DTR) provide means to assess transformer capacity in real time, enabling utilities to optimize asset utilization while maintaining insulation life and system reliability.

This paper reviews the historical evolution, fundamental principles, and current state of the art in transformer thermal ratings, and particular focus on DTR applications and standardisation. The development of transformer ratings is traced from the early years of the electrical industry to today’s advanced dynamic rating systems. We discuss the early practice of double ratings and their transition to single ratings in the early 20th century. The paper also examines the progression of thermal rating knowledge—from the first laboratory investigations to coordinated functional testing among multiple manufacturers—and pays special attention to the evolution of transformer loading guides issued by IEC and IEEE.

Modern transformer DTR approaches integrate hot-spot temperature estimation, moisture migration analysis, and variations in ambient conditions such as wind and precipitation to determine safe overload durations and condition -based loading limits. Key advancements include the incorporation of real-time sensor data, reverse calculation of permissible overload durations, and adaptation of standards to reflect new insulation materials and monitoring technologies.

By organizing the existing knowledge, literature, and best practices, this review highlights both the historical foundations and emerging methodologies underlying transformer DTR. The paper also shows the need in a common terminology for specifying DTR, supporting the evolution of advanced dynamic thermal models and the development of international standards that enable safe, flexible operation and extended transformer life in modern power systems.

16. **A. Pirker** (Verfahren Umwelt Management GmbH , Graz, Austria)**, F. Belavić** (Austrian Power Grid AG, Vienna , Austria)

ARTIFICIAL INTELLIGENCE AND CLASSICAL METHODS IN DGA INTERPRETATION - USE CASE ON A REAL TRANSFORMER DEFECT

Dissolved Gas Analysis (DGA) is a basis of transformer condition assessment. Classical interpretation schemes (IEC/IEEE guides, Duval methods, ratio and limit checks) are transparent and standardized, yet they often reach their limits in uncertain or mixed-fault situations and when monitoring variability blurs clear threshold violations. This paper presents a hybrid diagnostic framework that combines classical DGA interpretation with machine learning (ML) and anomaly detection to improve early warning capability and fleet-scale decision support using both laboratory and online-monitoring data. We present a real 1 GVA transformer-bank defect case study with a systematic ML evaluation trained by expertly labeled transformer records using transformer-wise stratified validation and explainable AI. Ensemble models (XGBoost and Extra Trees) demonstrate robust overall performance, they reveal a consistent diagnostic bottleneck for early-stage conditions. Some moderate samples are misclassified as normal, which is consistent with high feature overlap and elevated predictive uncertainty. In this case study, online DGA detected subtle changes in multivariate patterns earlier than classical thresholds. Subsequent offline electrical diagnostics (frequen cy response analysis and frequency response of stray losses) and inspection enabled the location of the fault before catastrophic failure. These results demonstrate the complementary nature of classical methods and AI: while standards -based diagnostics are essential.

17. **A. Gamil** (Hitachi Energy Germany AG, Bad Honnef, Germany)**, A. Al-Abadi** (Hitachi Energy Germany AG, Brilon, Germany)

COLD START APPROVAL OF NATURAL ESTER LIQUID FILLED POWER TRANSFORMER

In cold-climate offshore environments, natural-ester-filled power transformers face operational constraints due to higher pour points and early crystallization compared with mineral oils. This study presents a full-scale investigation of a 16.7 MVA / 66 kV transformer filled with a rapeseed-based natural ester and deliberately conditioned to −15 °C to assess cold-start performance during storage, energization, and loading. Spatially distributed fiber-optic sensors, tank-wall temperature pockets, and pressure measurements were used to quantify location-dependent thermal time constants, identify temporary solidification effects, and verify mechanical margins. After extended cold soak, energization at 110% revealed localized delays of ~4 h in winding and core-top liquid response, while dielectric properties and dissolved-gas behavior remained within natural-ester norms. Subsequent loading tests demonstrated stable KNAN→KFWF operation, practical pump-start thresholds near −5 °C, and top–bottom tank gradients up to ~12.8 K. An extended Dynamic Transformer Thermal Model captured the non-linear subzero behavior more accurately than a single-exponential approach, and CFD simulations provided physical insight into viscosity-driven circulation delays. The combined results establish phase-specific approval criteria for safe operation at −15 °C for this transformer design and highlight key parameters—local thermal inertia, stratification, and viscosity-dependent flow—that govern natural-ester behavior under cold-start conditions.

18. **M. Grisaru** (Marius Grisaru Oil & Transformer Solutions, Israel)**, V. Gurin** (Senior transformer expert, Ukraine)

BREAKDOWN VOLTAGE TESTING AS A MULTI-PARAMETER DIAGNOSTIC FRAMEWORK FOR TRANSFORMER RISK ASSESSMENT

Breakdown-voltage (BDV) testing remains the primary method for evaluating transformer insulating liquids, yet in routine practice, the result is reduced to a single pass/fail value. This paper proposes a standalone diagnostic framework that interprets classical BDV measurements more efficiently by combining the mean BDV, the coefficient of variation (CV%), and the minimum individual breakdown value, rather than relying solely on the mean. The central idea is that diagnosis should be linked not only to the measured values, but also to the relevance of the selected BDV method for the specific transformer case. Different configurations (electrode geometry, gap, voltage rise rate, temperature, oil-flow regime, hydrostatic pressure) exhibit different sensitivities to different weakness populations; a method that produces lower CV% is not necessarily the most diagnostically meaningful for every failure mode. A BDV–CV% risk matrix is proposed to map dielectric robustness onto maintenance actions. Field cases demonstrate that standard pass/fail thresholds overlook critical risks identifiable through this multi-parameter approach.

19. **G. Burk** (Ergon Inc. - Jackson Mississippi, United States of America)**, E. Casserly** (Ergon Inc. - Jackson Mississippi, United States of America)**, B. Pahlavanpour** (Ergon International Inc. – Waterloo, Belgium)

ADDITIVES AND OXIDATION IN ESTER-BASED INSULATING LIQUIDS – REQUIREMENTS AND ANALYSIS

The analysis and ultimate declaration of additives in insulation liquids and the oxidation stability requirements for insulating liquids are misunderstood subjects in need of transparency. The requirements for mineral insulating liquids, which have been in use for well over a century, are rather straightforward. The specifications were first published in 1969 under the International Electrotechnical Commission (IEC) as IEC 60296.

The use of synthetic esters has been well established, having been patented in 1981 and in service since then, for 45 years. The specifications were first published in 1992 under IEC 61099.

Natural esters are relatively newer, having been patented in 1999 and the specifications published under IEC 62770 in 2013 and ASTM D6871 in 2003. They have been in service for over 25 years. While there exists limited patent coverage for some specific formulations and applications, the general use of esters in electrical apparatus is well known and in the public domain. Multiple companies, in all regions of the world, are capable of producing products meeting the specifications in the international standards.

The product specifications (IEC 61099, 60296, 62770) detail the physical, chemical, and electrical properties of the insulating liquids. They also describe possible additives, the disclosure requirements of additives, and the applicable methods for the identification and quantification of the additives.

This paper will attempt to bring transparency to the various standards on insulating liquids, the identification and quantitative of additives, and the oxidation stability testing of insulating liquids. We will discuss the analytical test methods and results for the analysis of phenolic inhibitors in ester-based insulating liquids and on the oxidation stability of ester-based insulating liquids using standard test methods and expanded testing.

20. **H. Garg** (Hitachi Energy, Germany Hitachi Energy, Germany), **A. Al-Abadi** (Hitachi Energy, Germany), **I. Woyna** (Hitachi Energy, Germany), **D. Parmar** (Hitachi Energy, India)

MOISTURE ASSOCIATED DIELECTRIC CHARACTERISTICS OF SYNTHETIC ESTER-FILLED TRANSFORMERS UNDER VARIABLE LOAD CONDITIONS

This study examines moisture dynamics in the paper insulation of a synthetic ester-filled transformer under dynamic thermal and loading conditions. A computationally efficient modeling framework is developed and calibrated using heat run test data, enabling practical implementation in online monitoring and asset management systems. The framework forms the basis of the proposed dynamic transformer moisture model (DTMM), which resolves coupled thermal–moisture behavior while remaining suitable for real-time applications. The model explicitly accounts for the temperature-dependent solubility and diffusion characteristics of moisture in synthetic ester systems, allowing dynamic tracking of moisture migration between liquid and solid insulation. Multiple simulation scenarios are conducted to evaluate moisture evolution under different initial moisture contents, loading profiles, and thermal transients, highlighting the sensitivity of paper moisture to operational condition and short-term overloads. Eventually, to support improved insulation reliability, moisture management strategies, and predictive maintenance in ester-filled transformers. To characterize the moisture-dependent dielectric response of cellulose insulation, a modified Havriliak-Negami model is employed, capturing worst-case moisture scenarios and addressing the inherent challenges of real-time moisture prediction.

21. **C. Wang** (Hitachi Energy, China), **C. Jin** (Hitachi Energy, China), **A. Al-Abad** (Hitachi Energy, Germany)

DIRECT TEMPERATURE MEASUREMENT TECHNIQUES FOR HEAT RUN TEST OF DRY-TYPE TRANSFORMERS

The heat run test is a vital part of the factory acceptance process for dry-type transformers, traditionally employed to assess the average temperature rise of the windings under rated load conditions. However, this conventional approach fails to capture the precise location and magnitude of hotspot temperatures—key factors that influence insulation aging, thermal stress, and overall transformer lifespan. To address this limitation, this paper presents a comprehensive methodology for direct temperature measurement using a combination of thermocouples, platinum resistance temperature detectors (RTDs), and fiber-optic sensors (FOS). These sensor technologies were strategically deployed to monitor thermal behavior at critical locations during heat run testing. Based on the data obtained, the paper offers recommendations to improve measurement accuracy, enhance diagnostic resolution, and ultimately support higher product quality and reliability in dry -type transformer manufacturing.

22. **A. Al-Abadi** (Hitachi Energy, Germany), **W. Wu** (Hitachi Energy, USA)

EXTRACTING KEY THERMAL PARAMETERS BEYOND TOP LIQUID AND AVERAGE WINDING TEMPERATURE RISE FROM STANDARD HEAT RUN TEST

Heat run tests are critical for validating the thermal performance of liquid-filled transformers. The use of the double exponential equation to analyze resistance-based cooling curves significantly improves the accuracy of capturing the complex thermal behavior of transformer windings and insulating liquids. By leveraging measured resistance values, this method reveals two distinct time constants—associated with the winding and the liquid—as well as the liquid gradient. These parameters enable the estimation of axial winding-liquid temperature gradients, which are essential for assessing local liquid temperature rises within the winding structure. Such insights have direct implications for transformer design, operational reliability, a nd maintenance optimization especially during changing loading profiles. Moreover, the double exponential equation provides a robust foundation for developing advanced predictive models that account for the intricate thermal interactions between windings, insulating liquid, and other internal components of liquid-filled transformers.

23. **S. S H Ray** (POWER GRID Corporation of India Limited)**, G. Agrawal** (POWER GRID Corporation of India Limited)**, R. Srivastava** (POWER GRID Corporation of India Limited)**, N. Srivastava** (POWER GRID Corporation of India Limited)

IN-SITU REPAIR OF TRANSFORMERS AND REACTORS: A FIELD- VALIDATED FRAMEWORK FOR RELIABLE ASSET RESTORATION

India's rapidly expanding transmission network demands high availability of EHV transformers and reactors; however, factory-based repairs often encounter significant delays due to transportation constraints, limited OEM capacity, and extended refurbishment cycles. To address these challenges and minimize outage duration, a structured, engineering-driven methodology has been developed for executing major repairs directly at site. The approach integrates disturbance recorder (DR) evaluation, comprehensive low-voltage diagnostic testing, and internal inspections to accurately localize faults and define a precise repair scope. Reverse-engineered winding designs, stringent Material Quality Plans (MQPs), and controlled temporary repair environments are employed to ensure factory-grade quality during open-tank interventions.

Drying methodologies such as conventional vacuum and hot-oil processing, as well as low-frequency heating (LFH) are selected based on the severity of moisture ingress, with post-repair indicators such as moisture content, furan levels, and methanol/ethanol markers used to verify insulation health. Through multiple case studies, this paper illustrates the application of the methodology, including on-site replacement of a 315 MVA autotransformer winding, restoration of core shielding in a 420 kV reactor, and on-site winding replacement across six defective 400 kV shunt reactors. Post-repair diagnostics, including SFRA comparisons, DGA results, moisture measurements, and chemical marker analysis, validated the long-term reliability of all repaired units. The paper presents a practical, field-proven framework for site-based repair aimed at enhancing resilience, reducing lifecycle costs, and improving overall grid reliability.

24. **J. Novosel** (Končar – Power Transformers Ltd, A Joint Venture of Siemens and Končar, Zagreb, Croatia)**, M. Dorešić** (Končar – Power Transformers Ltd, A Joint Venture of Siemens and Končar, Zagreb, Croatia)**, I. Telalović** (Končar – Power Transformers Ltd, A Joint Venture of Siemens and Končar, Zagreb, Croatia)**, D. Švarc** (Končar – Power Transformers Ltd, A Joint Venture of Siemens and Končar, Zagreb, Croatia)**, H. Kordić** (Končar – Power Transformers Ltd, A Joint Venture of Siemens and Končar, Zagreb, Croatia)

INFLUENCE OF BACKGROUND NOISE ON NOISE MEASUREMENT ACCURACY OF REACTOR ENERGIZED BY TEST TRANSFORMER

Practical test environments are often affected by noise from external sources such as manufacturing processes, the test generator and other energized test transformers. In this case reactor of 150 MVAr is energized by test transformer of 280 MVA. Aim was to check influence on accuracy of measured noise values of reactor which operates in same operating point (at 100% rated voltage and 100% of rated current) when transformer operates in different tap position (different operating points). In different operating points transformer will have different values of voltage and current which highly effects noise level of the transformer as external source and therefore background noise. Measurement is performed with sound intensity method. The sound intensity method accounts for steady-state background noise but only up to a certain extent. With increasing levels of steady-state background noise, the measured sound intensity level of the test object decreases which is obviously unacceptable. Working within the limits for the P-I index as stated in 11.3.5 of IEC 60076-10:2016 maintains the acceptability of the measurement.

25. **M. Hillberger** (Austrian Power Grid AG (APG), Vienna, Austria)**, F. Belavić** (Austrian Power Grid AG (APG), Vienna, Austria)**, G. Steinmaurer** (University of Applied Sciences (FH OOE), Wels, Austria)

ANALYSIS OF TEMPERATURE MEASUREMENT SYSTEMS OF A POWER TRANSFORMER IN THE TRANSMISSION GRID

Power transformers in the transmission grid are exposed to loads that require accurate measurement of winding temperatures. This paper compares fiber optic hot spot temperatures directly measured using gallium arsenide sensors with conventional Winding Temperature Indicator (WTI)-based estimations derived from a thermal model and investigates the differences between both approaches. Operational data from a wind farm power transformer have been analysed for the period from July 2024 to February 2025. The results show that fiber optic measurement provides a more realistic representation of the thermal behaviour in the hottest winding regions. Compared to the sensor-based measurement, the WTI exhibits a slower dynamic response, systematically underestimates temperature peaks, and shows average deviations exceeding 10 K on both the high-voltage and low-voltage sides. A maximum deviation of 27.4 K is observed at the low-voltage windings at a load factor of approximately 85%. Under low-load operating conditions, however, the WTI overestimates the winding temperatures relative to the fiber optic measurement. This behaviour is attributed to transformer design aspects, reduced heat-loss conditions at low load, and structural limitations of the underlying WTI thermal model. A cross-correlation analysis reveals a systematic delay of 19 minutes in the WTI response compared to the gallium arsenide sensors. Model investigations using a constant load factor and subsequent parameter optimisation indicate limitations in the WTI parameterisation. The findings highlight the potential of fiber optic temperature measurement for a more accurate assessment of transformer thermal stress and underline its rele- vance for advanced cooling strategies and improved ageing models.

26. **W. Gil** (MIKRONIKA Poland)**, M. Andrzejewski** (MIKRONIKA Poland)**, M. Groński** (ENEA Operator Poland)

ONLINE CENTRALIZED SUPERVISION OF DISTRIBUTION TRANSFORMERS

Economic and technical conditions for electricity transmission and distribution are driving distribution system operators (DSOs) to implement advanced solutions for supervising the operation of power transformers with ratings ranging from a dozen to several dozen MVA. It is essential to expand monitoring, which has so far been implemented partially in dispatching systems (Network Management Systems, NMS). These systems monitor only basic transformer operating parameters, such as load currents, tap changer positions, and top oil temperatures. A pilot supervising system for medium power transformers, implemented at one of the distribution companies, provides transformer overload prediction in addition to basic monitoring functions. The TOP (Transformer Overloading Possibility) module, based on a transformer thermal model considers the impact of distorted windings' currents on heating. Ultimately, the system will monitor the condition of several hundred transformers and support dispatchers in managing power flow and the economical use of electrical energy.

27. **R. Niedermeier** (Maschinenfabrik Reinhausen, Regensburg, Germany)**,**
S. Ostrožnik (Kolektor ETRA – Technical Office, Ljubljana - Črnuče, Slovenia)**,**
M. Lohr (Maschinenfabrik Reinhausen, Regensburg, Germany)

EXPERIENCE WITH REMOTE SERVICE SOLUTIONS FOR TRANSFORMER ASSET MANAGEMENT

This paper explores remote service solutions for transformer asset management, highlighting their advantages in reducing downtime, optimizing resources, and enabling expert support across global sites. Challenges include language barriers and connectivity. Case studies demonstrate improved efficiency and reliability. The future promises expanded accessibility with advanced technology and universal digital infrastructure.

28. **A. Saveliev** (Maschinenfabrik Reinhausen GmbH, Germany)**, A. Schröder** (Maschinenfabrik Reinhausen GmbH, Germany)**, A. Kurz** (MESSKO GmbH, Germany)

MONITORING PRINCIPLES OF OLTCS IN POWER TRANSFORMERS

The On-Load Tap-Changer (OLTC) is used in power transformers to regulate voltage depending on load and power flow conditions. In recent years, robust and reliable vacuum switching technology has replaced the older breaking-in-oil switching technology. Although vacuum OLTCs are significantly more durable and have longer maintenance intervals, OLTCs remain a mechanical system, and a monitoring system can further increase confidence in its proper operation and thus extend maintenance intervals. Hence, monitoring systems remain indispensable in modern electrical power technology.

Since the OLTC is located inside the transformer and its parts are under high voltage, direct access to the relevant parts of the OLTC is limited. This inevitably makes the signal chain longer and more complex, requiring closer attention to the design of measurements and data processing. These considerations ultimately led to the development of a set of methods that we are currently use for OLTC monitoring.

The article presents the principles of building data processing systems and procedures that must be considered to ensure monitoring methods in such conditions. In order to obtain reliable output, when creating a monitoring system, it is necessary to ensure fundamental predictability of the behaviour of the measurement system. There must also be a way to describe the system mathematically and implement the model on a suitable device. The two approaches to system description, model-based and data-based, should not exclude a reasonable combination of these two principles.

The article presents Vibroacoustic Measurement (VAM) and torque monitoring methods, which are used as examples to demonstrate the rationale behind these principles. Both methods are based on completely different physical principles, and the principles of data processing and decision-making also differ significantly. Although both technologies serve the same purpose and are designed for OLTC monitoring, their different operating principles mean that they are complementary rather than competing. Each method covers different potential faults, so it is advisable to use both methods simultaneously.

29. **J. Sanchez (**EDF Division Technique Générale, France)**, S. Santos Da Silva** (EDF Division Technique Générale, France)

TRANSFORMERS BUSHINGS: CAPACITANCE DIFFERENCES BETWEEN FACTORY ACCEPTANCE TESTS AND ONSITE TESTS

Transformers' bushings are one of the most sensitive devices of power transformers. Above 100 kV, the bushings are commonly composed of capacitive aluminum layers, which are characterized by main capacitance (C1) and tangent delta measurements to assess it over time. These High Voltage (HV) bushings have been periodically tested by EDF since 2012, and the results of 715 field tests on 6 different bushing technologies, from 4 Original Equipment Manufacturer (OEM) are presented here. The main capacitance onsite measurements were compared to their Factory Acceptance Tests (FAT) references. The centile distribution difference between FAT and onsite tests presents a plateau, which is typical per each bushing technology and manufacturer. This difference is a key point to know for future assessments where FAT/marking plate values are compared to offline or online measurements, since it is not necessarily indicative of inner faults in the tested bushing.

30. **S. Keitoue** (Končar – Power Transformers Ltd, Zagreb, Croatia)**, T. Pavičić** (Končar – Power Transformers Ltd, Zagreb, Croatia)

A TECHNO-ECONOMIC MODEL FOR EVALUATING LOW-LOSS POWER TRANSFORMERS

This paper presents a techno-economic model for evaluating investments in low-loss power transformers based on transformer loss calculations and financial performance metrics. The approach integrates no-load and load loss characteristics with electricity price data, discount rates, and transformer lifetime to assess long-term economic performance. A structured methodology is proposed to calculate payback period, Net Present Value (NPV), and Internal Rate of Return (IRR) for different transformer designs. The model is applied to a representative high-power autotransformer using real electricity market data to illustrate the evaluation framework. In addition, a sensitivity analysis is conducted to demonstrate how variations in key parameters influence the economic assessment.

8. TIME-TABLE

Wednesday, May 06, 2026			
2:00 p.m.	-	8:00 p.m.	Arrival and Registration
			Tutorials:
2:00 p.m.	-	3:00 p.m.	**Limitations in Operation of High Voltage Equipment Resulting of Frequent Temporary Overvoltage's** **CIGRE JWG A3/A2/A1/B1.44** Convener: **Bartosz Rusek**
3:00 p.m.	-	4:00 p.m.	**Mechanical Properties of Insulating Materials and Insulated Conductors for Oil Insulated Power Transformers** **CIGRE WG D1.65** Convener: **Lars Schmidt**
4:00 p.m.	-	4:15 p.m	Coffie break
4:15 p.m.	-	5:45 p.m.	**Dynamic Thermal Behaviour of Power Transformers** **CIGRE WG A2.60** Convener: **Tim Gradnik**
6:00 p.m.	-	7:30 p.m	**Exibition 1:** **Technology Sponsor Event:** Get-Together at MR Stand: **100 years of Power behind Power**
7:30 p.m.	-	8:00 p.m.	Welcome Cocktail
8:00 p.m.	-	10:00 p.m.	Dinner
Thursday, May 07, 2026			
8:30 a.m.	-	8:50 a.m.	**Opening Session**
9:00 a.m.	-	11:00 a.m.	**Modeling And Simulation – Oral Session**
11:00 a.m.	-	11:15 a.m.	Coffee Break
11:15 a.m.	-	12:45 p.m.	**Modeling And Simulation – Poster Session**
12:45 p.m.	-	2:15 p.m.	Lunch
2:15 p.m.	-	4:15 p.m.	**Materials, Components and New Technologies – Oral Session**
4:15 p.m.	-	4:30 p.m.	Coffee Break
4:30 p.m.	-	5:15 p.m.	**Silver Sponsor panel discussion by Siemens Energy:** Stronger Together: **Building a Resilient and Sustainable Transformer Supply Chain Through Collaboration**
5:15 p.m.	-	5:45 p.m.	**Materials, Components and New Technologies – Poster Session**
5:45 p.m.	-	7:15 p.m.	**Exhibition 2:** **Bronze Sponsor Event:** Get-together at HAEFELY stand: **Transformer Networking Session with Selected Sparkling Wines**
7:15 p.m.	-	8:00 p.m.	**Presentation of Golden Sponsor KONČAR ELECTRICAL INDUSTRY Inc.**
8:00 p.m.	-	11:00 p.m.	**Golden Sponsor's dinner**

Friday, May, 08, 2026	
9:00 a.m. - 11:00 a.m.	**Transformer Life Management – Oral Session**
11:00 a.m. - 11:15 a.m.	Coffee Break
11:15 a.m. - 12:45 p.m.	**Transformer Life Management – Poster Session**
12:45 p.m. - 2:30 p.m.	Lunch
2:30 p.m. - 6:00 p.m.	**Excursion to Dubrovnik**
6:00 p.m. - 11:00 p.m.	Gala Dinner

Saturday, May, 09, 2026	
7:00 a.m. - 11:00 a.m.	Departure

9. REGISTRATION AND INFORMATION OFFICE

All participants should register immediately after arrival at the Registration and Information Office (in the Congress Centre of the Hotel Croatia Cavtat) where they will receive all conference materials and information regarding the Colloquium.

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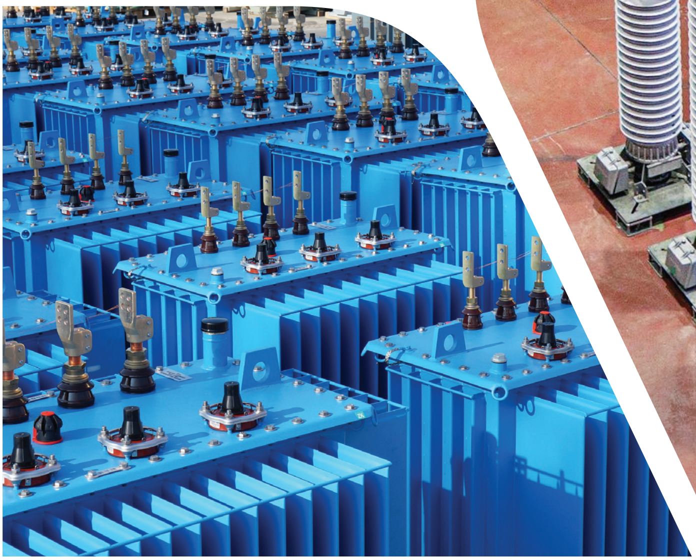

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