SPECIAL REPORT FOR SC A1
POWER GENERATION AND ELECTROMECHANICAL ENERGY CONVERSION

Special Reporters

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A few words about Session Papers

Session Papers focussed on a number of Subjects – referred to as 'Preferential Subjects' – selected in advance by the 16 Study Committees of CIGRE and available in the Call for Papers .
Session papers are selected through a two-phase review process – abstracts and full papers.
Have a look at the Technical Programme - the list of selected Papers for the Session and so have an overview of subjects that will be discussed. It is updated as Full Papers review proceeds.

And specificity of CIGRE Sessions

At CIGRE Sessions authors are given the opportunity to present their Paper during half-day specific meetings – the Poster Sessions.
Four days are also dedicated to 'Group Discussion Meetings' organised by Study Committees. Four meetings run simultaneously each day from Tuesday to Friday, under the presidency of the Study Committee Chairs. The purpose of these meetings is the discussion of the Session Papers on the basis of "Special Reports" which incorporate the gist of the Session Papers and raise a number of questions for discussion.
The Special Reports are available to all on free access – at the end of May - on the CIGRE website, on the Session page.
For fruitful discussions delegates are strongly encouraged to read the Papers before the Session.
The set of Session Papers is made available for downloading to all duly registered delegates before the Session through their private account on the registrations portal.
Papers are also readable on the Session smartphones application on site in Paris.
Follow our Session latest news and General Programme - by regularly visiting our website !

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INTRODUCTION

In 2024 CIGRE Study Committee A1 changed its name from “Rotating Electrical Machines” to “Power generation and electromechanical energy conversion” to better serve the evolving landscape driven by the energy transition.

The SC covers the full equipment lifecycle from research, development, design, manufacture and testing of power generation and electromechanical energy conversion equipment and their associated auxiliaries, through to commissioning, operation, condition assessment, maintenance, life extension, refurbishment, upgrades, efficiency improvement, conversion (e.g. from power generation duty to synchronous condenser/compensator duty), storage, and de-commissioning.

Within these fields, SCA1 promotes the international exchange of information, knowledge, practice, and experience, and adds value by synthesizing state-of-the-art practices to develop guidelines and recommendations.

For the 2026 Group Discussion Session, three preferential subjects were proposed to stimulate discussion considering the strategic directions:

• PS1 - Rotating Electrical Machines and the Energy Transition

• PS2 - New Machine Developments

• PS3 – Asset Management and New Challenges

A total of 57 papers have been accepted from 20 countries including 4 papers via the CIGRE Next Generation Network (NGN). The content of each paper is summarised below.

PARTICIPATING IN THE 2026 PARIS SESSION

You are invited to participate in discussing this Special Report at the SC A1 session held on **Thursday 27th August** starting at 08:45 in room **352AB** at the Palais des Congrès, Paris.

The reporters have compiled 24 questions; these are not specifically aimed at the papers’ authors but are synthesised from common issues and trends identified across the papers. This provides the opportunity for a broader response and participation in the discussion session.

The procedure for submitting contributions is detailed at the end of this report.

We encourage you to share your views and experiences in this unique CIGRE environment in response to the specific questions raised in this report. During the Group Discussion Meeting, each prepared contribution will be allocated a time slot of several minutes for a presentation followed by open discussion.

1. Preferential Subject 1: Rotating Electrical Machines and the Energy Transition

The preferential subject covers:

- Impact of the energy transition on the role, duty and flexible operation of rotating electrical machines
- Eco-design and sustainability
- Update of international standards for electrical machine requirements to reflect future applications

Eighteen (18) papers were accepted under PS1, but for the purposes of continuity within the Special Report, some were reassigned to a more appropriate PS. Therefore, ten (10) papers are summarised and discussed below related to the themes of PS1.

1.1 PS1 Paper Summaries

1.1.1 Impact of the energy transition on the role, duty and flexible operation of rotating electrical machines

Paper 10139 (France): ***Contribution of Large Synchronous Turbogenerators to RoCoF Mitigation in Low-Inertia Grids***

The paper focuses on the role and importance of rotating inertia in maintaining grid stability, and on the impact of non-synchronous power plants on the rate of change of frequency (RoCoF) during system disturbances or faults in low-inertia systems dominated by renewable generation.

After outlining the different methods used to assess the impact of RoCoF events on synchronous generators, the paper presents selected study results on RoCoF withstand capability, that is, the ability to maintain synchronism during a RoCoF event.

Large turbogenerator units can withstand RoCoF values of up to 1 Hz/s for 500 ms, or in some cases even higher values, provided that the point of connection to the grid is sufficiently strong to ensure unit stability.

A dedicated chapter of the paper considers the role of gas turbines in RoCoF mitigation, including the associated electrical and mechanical risks, and proposes strategies for mitigating these risks.

Paper 10141 (France): Contributions to stability through system inertia: a fair reconciliation mechanism for the European electrical system

Despite its crucial role in ensuring the frequency stability of the interconnected Continental Europe network, as well as the stability of each separated zone in the event of a grid split, the provision of inertia is not commercially remunerated in most energy markets.

The authors postulate that the provision of inertia in a large interconnected system may not be evenly distributed across all interconnected control zones (countries), and that some regions therefore benefit from inertia provided by others.

Based on this, the authors propose a remuneration scheme for inertia on an ex-post basis, in which the available normalized inertia in each area is compared with the amount of inertia considered necessary for stable operation of the overall system.

<u>Paper 10194 (India):</u> Synchronous Condenser Integration: A Green Grid Stabilisation Model for India's 500 GW Renewable Energy Vision

India is committed to achieving 500GW of non-fossil-fuel power generation capacity by 2030 as part of its decarbonisation efforts. A high share of inverter-based resources will reduce system inertia, short-circuit power, and voltage support, posing challenges for frequency stability, voltage control, protection coordination, and overall system stability.

The authors outline that India intends to install synchronous condensers at critical nodes of the inter-state transmission system in order to ensure stable and reliable system operation under the changing generation mix.

To identify the most critical locations, the local short-circuit ratio and the level of renewable energy penetration were compared qualitatively.

In the final chapter, the paper compares STATCOMs and synchronous condensers with respect to their key characteristics.

<u>Paper 10196 (India)</u>: Synchronous Condensers for India's Evolving Grid: Leveraging India's Retiring Generators for Reactive Power and Inertia Support

India has set a target of installing 500 GW of renewable energy capacity (non-fossil-fuel-based generation) by 2030, which is expected to meet 50% of its total energy requirements. Along with the retirement of conventional fossil-fuel generation at end of life, this will lead to reduced use of conventional synchronous generation and, in turn, to lower system inertia, short-circuit strength, and dynamic reactive power capability in the grid.

New synchronous condensers (SCs) offer a solution, but their deployment is constrained by cost, long lead times, and other factors.

The paper examines the feasibility and advantages of converting retired synchronous generators into SCs, offering benefits in terms of lower costs and shorter lead times.

<u>Paper 11447 (China):</u> Development and Application of Adding Synchronous Condenser Function to Turbo Generator

The paper describes the redesign and partial refurbishment of a 320MVA turbogenerator to enable its operation as a synchronous condenser. It reports the diagnostic measurements carried out ahead of the conversion to assess the condition of the equipment.

In particular, the rotor winding required redesign to meet the requirements for transient time constants. The innermost turn of each coil was replaced by a spacer.

The conclusion states that the overall process was successfully implemented and verified by measurements.

<u>Paper 11452 (China):</u> Research on the Application of High-Inertia Flywheel Energy Storage Condenser in High-Proportion Renewable Energy Power Systems

The paper describes studies carried out on the combination of a brushless doubly fed machine (BDFM) and a flywheel used as rotating energy storage.

Compared with full-size converter technology, doubly fed technology requires significantly lower converter ratings and thereby avoids active-reactive capacity crowding. Compared with mature DFIM technology, a key advantage of the BDFM is that no brushes are required. As the machine speed is independent of the network frequency, the concept of virtual inertia can be applied.

The authors developed a control scheme that allows independent control of active and reactive power exchange with the network, together with superimposed controls for primary frequency response (power droop), virtual inertia, and voltage control.

The developments were validated by simulation as well as on a 20kW testbed.

<u>Paper 11802 (Sweden):</u> Parameter-driven strategies to analyze fault ride through capability of synchronous generator

The paper describes an equation-based model developed for fault ride-through studies. The model uses a reduced-order two-axis representation of the synchronous machine.

After comparing the simulation results of selected cases to those obtained using commercial software, the model is used to study the correlation between several parameters and the critical clearing time.

The parameters studied include external reactance (system reactance), inertia constant H, transient reactance xd', excitation ceiling factor, transformer reactance Xt, power factor, as well as series and shunt braking resistors of different resistivity.

<u>Paper 11889 (Jordan):</u> Impacts of the Energy Transition on the Reliability and Operational Flexibility of Rotating Electrical Machines: A Case Study of the Operational Cycling and Reliability from the Samra Combined Cycle Power Plant, Jordan

The paper describes a study investigating the impacts on a Combined Cycle Plant in Jordan with a change in operation duty from baseload operation to cyclic duty, increased frequency of start-stops, rapid load following and reduced operating hours, as a result of increased renewable energy sources penetration on the power grid.

1.1.2 Update of international standards for electrical machine requirements to reflect future applications

<u>Paper 10820 (India):</u> Recommendations for Technical Standards for Synchronous Machines Co-located with Inverter Based Resources

This paper addresses the challenges encountered during compliance validation studies of the dynamic behaviour of a hybrid plant comprising wind farms, PV farms, and a pumped-storage plant with fixed-speed synchronous motor-generators.

In the case discussed, the ability of the PSP's synchronous machines to ride through the low-voltage ride-through (LVRT) envelope, expressed in terms of critical fault-clearing time, was found to be the limiting factor for the overall plant, while the voltage envelopes applicable to IBRs were applied.

Based on this finding, several options for improving the LVRT performance of the synchronous motor-generators are discussed, including adaptation of the machine design (Xd), optimisation of the excitation system parameters, including ceiling voltage and current, and support from shunt STATCOMs connected to the motor-generator buses.

The latter was found to be the most effective solution.

<u>Paper 11244 (Russia):</u> A Modern Russian Standard for Turbogenerators

The paper explains that the implementation of IEC 60034-3 as a national standard did not align well with the existing national standards framework and did not cover certain specific national requirements.

This led to the development of the Russian Standard GOST R 70940-2023, which is independent of the international framework but well integrated into the national standards regime.

The authors briefly outline the topics newly covered, such as reliability, temperature limits for structural parts, and static overload capability, as well as those revised relative to IEC 60034-3 and IEEE C50.13, such as inverse-sequence and sudden short-circuit requirements.

1.2 PS1 Discussion

Alongside the transition in the energy sources used for electricity generation, the electric power system itself is also undergoing major change.

The consequences are clearly visible. In some countries, power generation is already dominated by renewables, with many of the generating units being inverter-based resources (IBRs). For example, in Spain, shortly before the blackout last year, about 65% of generation came from IBRs.

The impact of such high IBR shares on system inertia is dramatic.

Many of the papers accepted by SC A1 address inertia, the consequences of reduced system inertia, such as increased RoCoF during disturbances, and technical solutions to overcome this challenge [10139, 10194]. These include converting retiring turbogenerators for synchronous condenser operation [10196], [11447], either as standalone units with the turbine decommissioned or as dual-purpose units capable of either active power generation or condenser operation by means of a clutch in the shaft line. Even the relocation of such retrofitted units to locations where they are more urgently needed is being discussed.

Paper [10141] highlights that different countries may pursue different decarbonisation strategies. Some may continue to rely on nuclear power and therefore face fewer inertia-related consequences in their energy systems or may even have more inertia available than is required for their own stability, allowing them to support other AC-interconnected regions or countries. The paper proposes a mechanism by which the provision of inertia as a system service could be remunerated within a large interconnected system comprising smaller control regions.

A consequence of reduced short-circuit power in the grid is a higher probability of deep voltage sags during disturbances, leading to low-voltage ride-through (LVRT) situations [11802]. The authors of [10820] show that such LVRT events are easier to manage for IBRs than for synchronous motor-generators. This means that insufficient short-circuit power can place the remaining synchronous generating units at risk of tripping offline. The authors also show that a STATCOM connected to the generator bus can support the synchronous machine during LVRT events.

Another interesting aspect of high IBR penetration, pointed out in [11452], is that the inverter controls of different IBRs across the system may interact adversely and promote complex voltage-frequency oscillations.

These challenges can be mitigated by maintaining, or restoring, acceptable levels of system inertia and short-circuit power, with the latter still being a distinctive capability of rotating machines.

It is encouraging that relatively new configurations of electromechanical energy converters, such as brushless doubly fed machines (BDFM), are also being investigated for flywheel energy storage condenser systems (FESCS), which can provide not only reactive power and voltage control but also control of active power exchange with the system [11452].

Finally, [11889] shows that not only the energy system is undergoing major change, but that existing assets must also cope with new challenges, such as operating regimes that accelerate equipment ageing as a result of increased flexibility requirements.

International / national standards may require updating to reflect modern operating regimes and grid requirements. [11244] describes an update to a national standard, whilst paper [10820] provides recommendations for defining separate requirements for projects where synchronous machines are co-located with IBRs which offer a practical basis for developing new technical standards and operational strategies.

As it can be seen not only from the discussed papers – a lot is going on but there's still much to be done.

1.3 PS1 Questions

[Q1.01] What experience does the community have in applying electromagnetic FEM on assessment of RoCoF or other aspects of machine – system interaction?

[Q1.02] What is the view of SC A1 on hybrid solutions involving (e)-Statcoms and synchronous condensers? Is there practical experience?

[Q1.03] Is the practice of retrofitting retired generators to synchronous condensers applied in a broader scale also outside India?

[Q1.04] To what extent are customer/grid regulations requiring machine design adaptations/optimisations which are outside the constraints given in the international standards (e.g., IEC60034-1 and -3, and IEEE C50.10/C50.13) and would an update to those standards be deemed helpful / necessary?

[Q1.05] While the market for ancillary services has been an active topic for discussion for almost 30 years, have any practical mechanisms been developed or applied? Has the provision of system inertia ever been considered as a marketable quantity?

2. Preferential Subject 2: New Machine Developments

The preferential subject covers:

- Technology developments for wind generators, variable speed pump-storage, synchronous compensators and SMR applications
- Improvements in design, manufacture, efficiency, insulation, cooling, bearings and materials
- Enhancements in the performance, reliability and control of rotating electrical machines

Sixteen (16) papers were accepted under PS2, but for the purposes of continuity within the Special Report, some were reassigned to a more appropriate PS. Therefore, twenty (20) papers are summarised and discussed below related to the themes of PS2.

2.1 PS2 Paper Summaries

2.1.1 Technology developments for wind generators, variable speed pump-storage, synchronous compensators and SMR applications

Paper 10142 (France): Type test of the largest commercial 4-pole generator and exciter for a EPR power plant

The paper discusses the type test of a very large 2235MVA generator for a European Pressurised Reactor (EPR) nuclear site and describes the requirements with reference to the applicable standards. The correspondingly large brushless exciter is also qualified, which has a short term power output of 23MW, above its continuous rating of 5.8MW. The paper compares how closely the calculated parameters matched those determined during the type tests. It found good correlation between the two. It confirms the feasibility of the high output turbogenerator in accordance with the IEC and the purchasers specification.

Paper 10819 (India): Enhanced Static Excitation System architecture for high-capacity Turbogenerators with improved current sharing and harmonic performance

The paper analyses the limitations of conventional static excitation systems used in large turbogenerators, particularly current imbalance among parallel thyristor bridges and high harmonic distortion caused by common AC/DC bus architectures. It proposes a modified excitation architecture using a multi-winding excitation transformer, feeding independent thyristor bridges, forming a 24-pulse rectification system. The paper discusses that the complexity of such a system is deemed to be offset by the advantages of improved harmonic performance and enhanced reliability. Simulation results show improved current sharing among bridges utilising the proposed architecture, with a significant reduction of harmonic distortion, resulting in a decrease of the HV side current's total harmonic distortion from 26.64% in the conventional configuration to 0.94% in the proposed architecture.

Paper 11253 (France): Features of Akkuyu NPP Turbogenerator's Brushless Exciter and Factory Test Results

The paper describes features of a brushless exciter for the Akkuyu Nuclear Power Plant, which is the first nuclear build under construction in Turkey; comprising of four turbine generator units. The paper discusses the requirements of the design with details of the acceptance tests to meet the Turkish grid requirements. Qualification of the design has been presented, including

the special design considerations for nuclear sites, such as seismic studies through calculation. The comprehensive tests showed good correlation with the original calculation tools used.

Paper 11351 (Spain): Model Validation of Full-power Converter Variable Speed Hydro Generators

Two units at Torrejon pumped storage hydro station are being converted to variable speed operation. This aims to increase the operating head range, increasing the storage capacity to 210GWh. The modification requires compliance with the European Network Code, which stipulates that steady-state and dynamic models are provided and validated. The authors have developed a fundamental model as an alternative to those of the original equipment manufacturers, which are encrypted. It has been successfully validated against the calculated results from the manufacturer's model. A reduced order model was proposed and also validated against measured data taken during commissioning of one of the converted hydro units.

Paper 11449 (China): Development and Engineering Application of Key Technologies for Baihetan 1000 MW Fully Air-Cooled Hydro-Generators

This paper describes the challenges and solutions adopted on the 1,000 MW units for the Baihetan Hydropower Station in China, which is the country's second largest hydro plant with 16GW of installed capacity. The paper describes the challenge of fully air cooling the large generators with a 24kV insulation system. Typically, units of this size would utilise water-cooling or evaporative cooling to control the temperature rises. Details of models and tests are provided, giving an interesting insight into the work required to develop the generators.

Finally, the paper stated that operational data has fully validated the performance of the machines, which fully meets stringent engineering standards.

Paper 11451 (China): Development of a high thermal conductivity air-cooled generator fabricated by GVPI technology

The paper discusses an improvement of the thermal properties of High Thermal Conductivity mica tape used in air cooled generators. Boron nitride was introduced to the mica tape to enhance the thermal conductivity for use in global vacuum pressure impregnated machines. The paper describes a combination of the theoretical modelling, of the properties of the Boron Nitride containing mica tape, and the experimental classification of the main insulation system's thermal, electrical and mechanical properties. This is followed by fibreoptic-based verification of generator stator hot-spot temperature and demonstrates the reduction achieved utilising the new insulation system.

A mica tape with Boron Nitride loading of 30 g/m2 was preferred as the optimal; and was used for verification tests. With a higher loading of Boron Nitride, there was found to be diminishing returns on the thermal performance. The heat transfer is discussed as being approximately 33% higher than conventional insulation systems, which is considered a substantial improvement.

Paper 11952 (Germany): Underexcited saturation state in cylindrical rotor synchronous machines

The paper describes in detail the saturation effects during under-excited operation. Historically the design of round rotor generators was based on the expectation that the generator would mostly operate in the overexcited condition, thus the overexcitation limit of the machine was based on the conservative assumption of an unsaturated machine. However, in recent times with a larger penetration of renewable generation, generators are required to operate mostly in the under-excited region. This is stated as being closely related to the grid infrastructure, with

particular mention of high voltage cables which have high capacitive characteristics. This pushes voltages higher when under light load, requiring compensation.

The paper investigates and demonstrates that the generator operating in the under-excited region does have some saturation effects that influence radial flux losses, pressure finger losses and core and end teeth losses. Using the appropriate saturation state to evaluate the under-excitation limit allows the expansion of the operational range, with the understanding that it is required to establish thermal limits as well.

Paper 11953 (Germany): Development and design of a 390 MVA / 600 rpm air-cooled motor-generator

The paper describes the development of indirect air cooled pumped storage motor-generators with an output rating of 389MVA and rotational speed of 600rpm. Which is being implemented for two units at the Chan Long Shan Pumped Storage Station. These machines require a large number of start-stop cycles of 10 per day for 50 years. The requirement for the turbine was driven by the high head of 764m, with higher speeds resulting in a more compact machine size.

The paper describes the design development and evaluation of the motor-generators and that typically such high MVA rating and high speed would previously only be equipped with direct water-cooled windings for the stator and/or rotor.

Paper 12595 (Sweden): The integrated damper winding behaves like a continuous classic damper winding during sudden short circuits in large, saturated hydro generators

The paper investigates the behaviour of integrated damper windings in large salient-pole hydro generators during sudden short circuits. It proposes a method to evaluate the sub-transient reactance Xq" and the ratio Xq"/Xd" by analysing current waveform shapes during the first milliseconds after a sudden three-phase short circuit.

The approach is validated using measurements from five hydro generators, in the range of 50 to 170 MVA and 100 to 200 rpm and is supported by 2D and 3D finite-element simulations and analytical modelling of pole-to-pole impedance.

The results show that for machines with integrated damper windings the inductance ratio decreases with increasing saturation and approaches the values of machines with a continuous classical damper windings at rated voltage.

The authors consider that this method offers advantages over the current methods for calculating Xq within the IEC and IEEE standard suite.

Paper 12615 (Spain) [NGN]: Saturation effects on synchronous generator reactive power limits: comparison of constant reactances and precise methods

The papers discusses the challenge of accurately determining real-time reactive power capability of synchronous generators with high renewable penetration. Typical approaches neglect the dynamic magnetic saturation which can overestimate the generators capability.

The results show that incorporating a precise dynamic saturation model substantially alters the generator's capability envelope. The most pronounced effect appears in the over-excited region, where the maximum reactive power limit is significantly reduced. The paper discusses the effect on the active power operating point, and the transformer tap position which also introduces notable asymmetry. The results show that dynamic modelling is essential for accurate and operationally meaningful reactive power limits in modern systems. The proposed solutions align with the requirement for generators in Europe. It offers what is considered by the authors

to be a more realistic capability envelope to support voltage control with higher renewable penetration in modern electrical transmission grids.

2.1.2 Improvements in design, manufacture, efficiency, insulation, cooling, bearings and materials

Paper 10143 (France): Calculation of Overpressure in the Enclosure of a Hydroelectric Generator during a Phase-to-Phase short circuit with electric arc

This paper presents a comprehensive study comparing two different methodologies to estimate the overpressure generated by internal arc faults when applied to enclosed hydrogenerators. One method is based on the Report 602 issued by CIGRE Working Group A3.24 for switchgear. The other method was developed by a utility and is an analytical model to estimate arc voltage as a function of arc current and electrode gap.

Both methods were benchmarked against a series of electric arc tests that were conducted. The paper discusses that the utility model for arc voltage level demonstrates higher accuracy across a wide operating range and results in significantly higher voltages than the default model proposed by the CIGRE working group.

The proposed model provides a validated framework for assessing and mitigating the effects of internal arc faults in enclosed generators, enabling improved design for safer generation systems. The paper proposes mitigation methods to limit the overpressure in the event of a phase-to-phase short, resulting in safer and more resilient generator designs.

Paper 10185 (USA): Slot Conductive Coatings for Electrical Contact Control in High-Voltage Generator Stator Windings

The paper provides a practical analysis of how slot conductive coatings in generator stator windings degrade over time. It focuses on the two dominant mechanisms: “bleaching” caused by partial discharges and spark erosion caused by mechanical vibration and intermittent contact. It explains how these mechanisms originate, how to distinguish them in the field and why proper diagnosis is essential to ensure effective repairs. In addition, the paper presents a field-validated repair method to stabilise any degraded area. The paper highlights that when appropriate coating restoration methods are utilised, stabilisation occurs resulting in significantly reduced further degradation. This results in extending winding service life, helping avoid costly rewinds and interventions.

Paper 10218 (USA): Thermal Cycling of High-Voltage Generator Stator Windings: A Comparative Study of IEEE 1310 and IEC 60034-18-34 Using Simulation and Testing Experience

This paper outlines an interesting comparison between the IEEE and the IEC standards for thermal cycling tests. The paper detail that both standards differ significantly in their test procedures and highlights the major differences. Furthermore, the paper raises important questions regarding the realism of the test setups, the repeatability of the procedures, and the appropriate acceptance criteria, which is highlighted as being a current and crucial discussion within the IEEE 1310 working group.

The paper also state thermal cycling tests could artificially initiate defects if thermal and mechanical boundary conditions deviate from realistic generator operation. The difficultly correlating real world experience with thermal cycling tests is discussed, and that a real world dataset supported by statistics would be a logical next step for the standards to explore.

Paper 10219 (USA): The Gradient Coating Systems for Electrical Field Control in High-Voltage Generator Stator Windings

This paper discusses the stress grading system, its purpose and design. It describes the historical approaches once applied in the industry, such as Asbestos, and also highlights certain development routes that did not endure, resulting in the current main technologies, such as Silicon Carbide coatings. Theoretical and practical considerations are discussed, which describes what conditions these coatings must endure.

There are practical examples provided of degradation in the field, with the paper highlighting the difficulty in assessing these areas during visual inspections.

Paper 10754 (Japan): Theoretical and Experimental Evaluation of Hot-spot Temperature at Series Connection of Turbine Generators

The paper describes the studies carried out on an indirectly air-cooled generator stator winding to explain why some endwinding connections showed signs of overheating after several years of operation. The pattern of overheating, and the sporadic distribution of the hot spots could not be explained by previous studies.

A hypothesis was formed that the combination of strand resistances could be causing localised high temperatures. Calculations and mock up test pieces were produced to verify the likely cause of the hot spots. It was concluded that the variation in operational temperatures was due to the circulating current within the stator bars, resulting from the varying resistance between the adjacent brazed strands.

The design was subsequently improved to use copper plates to join top and bottom bar strand stacks, in order to have a more consistent electrical contact. The Roebel transposition was increased to 540° from 360° and an insulation cap was applied with a thermally conducting filler to achieve a more homogeneous insulation arrangement with correspondingly better thermal conduction. The resulting improvements were demonstrated to substantially reduce peak temperatures.

Paper 10782 (Brazil): Insulation Systems for Motors, Generators and Synchronous Condensers – Contributions to Writing Stator Winding Design Specifications

The paper describes the different insulation systems employed when building generators, highlighting a number of instances were misconception or misinterpretations of technical concepts has impacted the reliability of machines. It provides a broad and general overview on available Insulation Systems and how this topic might be discussed during new builds or refurbishment negotiations between supplier and buyer.

Due to the complexity of the overall topic "insulation" there is no one solution or technology that fits all scenarios, there is a need to balance many aspects to realise the most appropriate and long lasting solutions. If not done correctly it can result in overly specific technical requirements which can push the design outside the manufacturers expertise.

The paper discusses the need for a cohesive approach which draws upon empirical knowledge, service experience and robust testing. Ultimately this is discussed as allowing the end-user to better achieve their objectives. The authors state that “open dialogue, mutual respect for expertise” are essential and that the collaborative approach is to be in the best interest of both parties.

Paper 11954 (Germany): Comparison of HV-Insulation system acc. IEC 60034-18-42 for a hydro-generator with different inverter technologies

The paper discusses HV insulation systems according to IEC 60034-18-42. With focus on the properties of the stress grading tape used in converter fed synchronous machines and doubly fed induction machines. The paper describes hot-spot formation and location, using thermal imaging, depending on the classical AC voltage or bipolar rectangular inverter voltage. The latter having a significant influence on the temperature developed during operation.

The introduction of Modular Multi-level Converters has brought benefits due to scalability, efficiency and flexibility. However, this has introduced several challenges and additional stresses on the Stress Grading systems utilised in generators due to the significantly higher switching frequency of up to 10kHz. Faster switching could be seen to produce higher temperatures in the stress grading hot spots, due to inverter induced stress.

The paper concludes with a recommendation that the IEC 60034-18-42 is updated to reflect some of the developments within the industry. The paper highlights the trend towards faster switching, which it concludes will have a negative impact on the generator stress grading temperatures in operation.

2.1.3 Enhancements in the performance, reliability and control of rotating electrical machines

Paper 10180 (USA): A Relative Harm Index Framework for Quantifying and Mitigating Circulating Currents, Harmonics and Supra-Harmonics in Wind Turbine Drive-Train Reliability

The paper discusses circulating currents in on-shore wind turbine generations, which are typically standard induction or doubly fed induction generators. Main bearing failures have been a known issue for over 15 years, with investigations revealing high circulating currents at fundamental, harmonic and up to supra harmonic frequencies. Shaft currents, some exceeding 150 amps have been measured, which is considered to be the root cause of approximately 60% of the failures of the main bearing.

The paper discusses the relative harm index (RHI) which has been developed to help operators evaluate the risk present. The assessment allows the identification of the severity, such that appropriate mitigating actions can be taken, which are also discussed.

Paper 10784 (Brazil): Heterogeneous Air Gap and Its Consequences Modelling Residual Magnetic Attraction Force

This paper discusses the residual magnetic attraction force, also known as unbalanced magnetic pull in hydro generators. A number of case studies which resulted in material cracking and structural failures are described. Modelling has been proposed which enables early detection and assessment of the risk on vertical hydro generators.

The development of a practical analytical framework with two levels of modelling: a complete model based on magnetic flux density distribution which requires complete geometric information, and an expedited model, intended for situations where full machine geometry is unavailable. It is common that the full geometry is not available, which is why the simplified model has been developed. This is stated as having provided practical use and provided faster realistic assessments in the absence of full machine data.

<u>Paper 11551 (Sweden):</u> Lessons learnt from actively balancing two units magnetically with rotor segmentation and dedicated power supplies which results in resolving vibration issues

This paper describes the main issues related to or caused by unbalanced magnetic pull in salient pole synchronous machines. It introduces the concept of active magnetic balancing (AMB) for salient pole machines, which is described in detail. This enables the unbalanced magnetic pull to be actively managed with the injection of current to directly counteract the effect. It can theoretically be applied to any generator with 4 or more poles. The case studies provide real world examples of the approach and were shown to have up to a 70 percent reduction in vibration levels.

2.2 PS2 Discussion

The papers this year provide extremely detailed technical analysis of their chosen submissions, offering interest to all aspect of A1 . The detail, knowledge and the depth of the papers is truly commendable and will give readers insight into a technically diverse range of generator topics. The focus on improving the industry is clear, in that respect the papers have all added knowledge to the group.

Multiple papers discuss the testing of either new machines or novel analysis of generators and their systems. Showcasing the communities problem solving and requirements for new machines or making existing plant more resilient. There are several underlying themes throughout the presentations in this year's submissions with the following highlights:

- A number of papers raised the impact of unbalanced magnetic pull on salient pole hydro generators. The contrasting approach between the papers from modelling, to understand the severity, to a novel active electromagnetic balance system to mitigate the impacts of the unbalanced forces.
- Multiple papers explored modelling techniques for design, problem solving and assessment of operational risks. These papers discussed multiple different topics and approaches. For example, damper circuit design, assessment of the likelihood of failure of machines and offering greater operational ranges due to better understanding of the machine parameters. Utilised at all stages of the machines life, from design, operation to uprating and repairs.
- The effect of modern power electronics on insulation systems has been raised, the appropriateness of current methods for the validation testing of insulation systems, as well as the resulting degradation from electrical wear mechanisms on the physical stator. Combined together these provide insights across the full lifetime of the stator windings from conception to end of useful life.
- Previous Paris sessions in recent years have seen papers on negative excitation current to increase the under excited reactive range. This year's papers has seen a number of papers which explores the modelling of saturation effects on standard generator charts, which can underestimate the under-excited capability. Highlighting the market forces driving this requirement and desire to deliver increased reactive range due to renewable penetration into transmission systems.

2.3 PS2 Questions

[Q2.01] Due to the impact of operating conditions from external sources, such as increased reactive capability demand, are users and service providers seeing a corresponding increase in findings during inspections? For example, heating damage to windings, core etc.?

[Q2.02] High thermal conductivity coatings, larger machines which are fully air cooled, are pushing the technical boundaries of insulation systems further than has been achieved previously. What are the expectations of the community from a longevity perspective, is there a greater requirement for monitoring insulation systems for degradation? If so, what are users doing and conversely what are manufacturers and repairers suggesting be carried out?

[Q2.03] Multiple papers raised thermal cycling testing and its limitations and applicability for certain applications. Multiple operators now have requirements for multiple start / stop cycles per day, often combined with faster ramp rates, high reactive power and higher harmonics. Which all places additional stress on the insulation systems:

- What are end-users doing or what should they be doing from a specification standpoint to ensure reliable operation throughout the design life?
- What are manufacturers seeing and what should they be doing to ensure the same?

[Q2.04] To what extent is the calculation of the pressure rise within the generator cubicle / ring room as a consequence of an (internal) arc fault an industry standard? Which methods or procedures are applied? As the dimensions and the masses involved heavily differ from switchyard cubicles, where the calculation and validation of pressure rise is state of the art, is there any validation of methods applied specifically for generators?

[Q2.05] With the increase in applications of variable speed hydrogenerators, efforts are underway in IEC to address the technical specifications of such machines. Are there any limits or specific requirements peculiar to the operation of variable speed hydrogenerators on the system?

[Q2.06] Traditionally, the application of variable frequency drives has been relatively limited in utilities. However, the increase in application of adjustable speed hydrogenerators demonstrates that the implementation of these technologies will increase in the utility sector. What is the awareness of utilities of the advantages and possible downsides of inverter fed drives?

[Q2.07] What is the communities experience on the use of wind turbine generators and how reliable are they compared to conventional gas/steam turbine driven plant?

- What are the main failure modes being seen and what are the typical failure rates across large farms?
- Is there an influence of long-term service agreements on the decision to repair or replace?

[Q2.08] The surge in demand for power generation equipment has been largely driven by datacentre projects for which small modular reactors (SMR) are presumably not considered suitable. What is the foreseen duty of SMR power plant and what special design features, operating duty, load profile and service lifetime requirements are being requested which vary from conventional applications?

3. Preferential Subject 3: Asset Management and New Challenges

The preferential subject covers:

- Digital twin: Condition monitoring, diagnosis, prognosis of rotating electrical machines including the use of artificial intelligence, deep learning techniques, Industry 5.x requirements
- Improved maintenance practices to ensure power supply reliability
- Extending operational performance and service life of installed base

Twenty-three (23) papers were accepted under PS3, but for the purposes of continuity within the Special Report, some were reassigned to a more appropriate PS. Therefore, twenty-seven (27) papers are summarised and discussed below related to the themes of PS3.

3.1 PS3 Paper Summaries

3.1.1 Digital twin: Condition monitoring, diagnosis, prognosis of rotating electrical machines including the use of artificial intelligence, deep learning techniques, Industry 5.x requirements

Paper 10789 (Brazil): Assessment of the Electrical Insulation of the Stator Windings of a Large Hydrogenerator

The paper describes complimentary off-line and on-line testing to assess the electrical insulation of the stator winding of a large 350 MVA hydrogenerator. The assessment was triggered by an abnormal increase in partial discharge activity observed in on-line monitoring data. Different electrical insulation tests were carried out to try and localize the fault.

Conventional insulation resistance and dielectric response tests indicated acceptable global insulation conditions. Sweep Frequency Response Analysis (SFRA) did however indicated a difference in the frequency response curve of one of the stator phases compared to the others.

Visual inspection confirmed the presence of mechanical damage, which after removing the insulation revealed severe thermal degradation on the bar surface and rupture of a rectangular phase connection ring at the back of the endwinding. The fault was repaired and consecutive electrical tests demonstrated a significant reduction in partial discharge levels and the restoration of normal operating conditions.

The main contribution of the paper is the sharing of procedures and results in localizing electrical insulation faults in hydrogenerator stators as a result of an abnormal increase in partial discharge activity observed in on-line monitoring data.

Paper 10792 (Brazil): Performance Analysis of Electronic Components and Digital Systems in Modernized Hydroelectric Power Plants

The paper describes a study to analyse the performance and failure rates of electronic components and digital systems used in the control and protection of hydro electromechanical plant and to determine the service life of these components and systems following modernisation.

The study is based on three hydroelectric power station located in southeast Brazil. These plants underwent complete modernization 15 years ago and had been showing an increase in failure rates in recent years, resulting in unplanned outages and generation unavailability. A significant

number of failures were identified in the electronic cards of the voltage regulators and speed governors, as well as in the digital microprocessors responsible for monitoring the equipment associated with the turbine.

The results of the analysis indicate reduced service life for certain components and systems. The proper functioning of electronic devices and digital controllers is fundamental for the full operation and reliability of the plant. Consequently, they require special attention, either through performance monitoring or periodic technological upgrades via a second partial modernization for specific electronic components as well as for the supervision and control systems.

Paper 10797 (Brazil): ***Partial Discharge Monitoring Experience in Bulb Generators***

This paper demonstrates how online partial discharge (PD) monitoring can enhance asset management strategies for hydroelectric power generation fleets.

Using the Pimental hydroelectric power plant as a full-scale case study, the authors demonstrate that long-term PD trend data enables a transition from time-based to condition-based maintenance, improving failure prediction and reducing unplanned outages.

Through distinctive PRPD patterns and trend deviations, this study demonstrates the ability of PD monitoring to identify multiple defect types, including corona activity, oil or metal contamination, and moisture intrusion due to cooling system leaks. Furthermore, the study highlights emerging operational challenges, such as the significant impact of humidity on PD behaviour, highlighting the need to incorporate environmental conditions into asset health assessments.

By documenting the PD evolution of a bulb-type generator from start-up, this study provides valuable insights for building asset health indicators, optimizing maintenance plans, and managing complex modern power generation assets.

Paper 10801 (Brazil): ***Case Study: Vibration Analysis for Detection of Unbalanced Magnetic Pull and Dynamic Eccentricity in a 200 MW Vertical Kaplan Turbine***

This paper discusses and demonstrates that vibration analysis is an effective tool to identify dynamic eccentricity associated with Unbalanced Magnetic Pull (UMP) in large vertical synchronous hydrogenerators.

It presents a case study of vibration-based analysis of dynamic rotor eccentricity associated with Unbalanced Magnetic Pull in a 200 MW vertical Kaplan hydrogenerator. Since no online air gap sensors were installed on this unit, direct measurement of air gap variations during operation was not available for the study. The detection and assessment of rotor eccentricity were therefore performed indirectly, based on relative shaft vibration signals from the proximity probes installed at the generator guide bearing in accordance with ISO 20816-5.

In this case study, the observed behaviour was diagnosed as UMP-driven dynamic eccentricity, aggravated by stator deformation, loss of vertical alignment, and non-uniform stiffness in the generator guide bearing caused by asymmetric pad clearances.

The installation of online air gap sensors is recommended for future condition monitoring upgrades.

Paper 10821 (India): AI-Augmented Multi-Test Diagnostic Framework for health indexing in Hydro Generator Fleets

The article introduces a hybrid diagnostic framework aimed at improving insulation condition assessment in hydro generator fleets. Traditional diagnostic approaches often rely on isolated thresholds and expert judgment, which can lead to inconsistent interpretation across units with different ages, environments, and maintenance histories. The authors address this issue by combining rule-based, normalised and weighted scoring of test results, aligned with established standards and utility practices, with AI-augmented framework using a two-layer decision support system trained on historical fleet data to create a more accurate and standardized Health Index (HI).

The method takes into account not only the absolute values of the insulation parameters of individual off-line tests (IR/PI, PD, tan delta etc.), but also trend analysis, previous maintenance activities, and, by applying machine learning methods, determines the overall health index of the machine. The systematic feature fusion across generators enables consistent differentiation between ageing, moisture ingress, and incipient defects, while remaining fully interpretable for utility engineers and asset managers.

Case studies from units in service are presented to illustrate the methodology and demonstrate its value in improved prioritization: machines initially flagged as critical by rule-based criteria were correctly downgraded following recent refurbishment, while units showing slowly increasing PD activity were identified early as emerging risks despite otherwise acceptable test values.

Paper 11352 (Sweden): Applied use of AI for stator winding insulation diagnosis using online PD monitoring

This paper introduces an online partial discharge (PD) monitoring tool to help separate noise from stator winding PD and identify PD patterns and possible sources.

It combines automated clustering algorithms with neural network models using CNN (convolutional neural network) classification model for defect identification and classification. Clustering distinguishes different PD pulse sources, while AI handles pattern recognition and diagnostics.

The model was trained using thousands of data samples, some of them measured in real world assets, and some created synthetically from the available PRPD charts collected from inspection records. Data augmentation techniques were also used to create a larger dataset.

After validation in the laboratory, the tool was used to analyse the stator winding insulation status in 19 real rotating machines and demonstrated promising results. Future improvements in the model predictions will be achieved by retraining the model with additional data from a greater variety of PD sources and different sensor configurations.

Paper 11790 (Croatia): Advanced Machine Learning-Based System for Predictive Monitoring and Early Fault Detection in Dubrovnik Hydropower Plant

The paper presents an advanced monitoring and diagnostic system enhanced with an added machine learning module to detect deviations from the normal operating range of selected operating parameters in hydropower generators far earlier than conventional methods.

The model was successfully implemented on two units of the Dubrovnik Hydropower station and has been running since July 2024

The deployed model is set to predict the vibration parameters of a maximum shaft displacement, Smax1, in each of the radial bearing planes but also integrates other specialized sensors. The monitoring system is connected and integrated into the SCADA system from which process and operational parameters are obtained. The module uses this and environmental data to provide multi-horizon forecasts and a new Key Performance Indicator (KPI) that forecasts generator behaviour over four future time horizons (1 hour, 1 day, 1 week and 1 month).

The paper provides details of a case study carried out to verify the system using historical data from 2020 to 2021 recorded during a period when a unit in a similar hydropower plant experienced an increase in turbine-bearing vibration. In the study, the monitored output variable was the extracted shaft displacement amplitude of the first harmonic at each guide bearing. It is stated that, by using this system, the increasing trend in bearing vibration could have been detected up to 47 days before the failure occurred.

Paper 11971 (Canada): New VHF Technology for Separating Partial Discharge Sources in Operating Stator Windings

This paper introduces an advanced VHF-based online partial discharge (PD) diagnostic technology that enhances reliability, reduces expert dependency, and strengthens condition-based maintenance strategies. The work addresses one of the key challenges in asset management: the difficulty of correctly identifying PD root causes using traditional PRPD patterns, which often require expert interpretation and may lead to misdiagnosis.

The newly developed system automatically separates PD sources—phase-to-ground, phase-to-phase, and cross-coupled signals—using nanosecond-resolution pulse acquisition and real-time logic processing, eliminating the need for manual clustering or AI tools, which have shown limitations in stator-winding diagnosis.

Demonstrations on operating hydro and turbine generators show that the method reliably distinguishes noise from true winding PD and clearly identifies the degradation location, enabling more accurate maintenance decisions, optimized repair prioritization, and improved lifecycle asset management.

Paper 12331 (Serbia): Stress-Aware Maintenance Intelligence System (SAMIS) of Synchronous Generators

This contribution presents the Stress-Aware Maintenance Intelligence System (SAMIS), an analytical framework implemented as an analytical layer within existing utility-wide SCADA and centralized data platforms without introducing additional sensors, protection logic, or real-time control loops.

Using existing SCADA, archived data, and event-log data, the system provides a SCADA-based electro-thermal reference model and applies stress-aware indicators linking operating regimes to cumulative aging. A unified decision-support architecture combines physics-based assessment and structured human observations to derive stress-aware health indicators and provides a transparent, physics-based foundation for maintenance prioritization across the generator fleet.

The system has not yet been deployed as a permanently operating online system across a generator fleet. Engineering validation has been performed through representative operating scenarios derived from real measurements and test campaigns on four nominally identical hydro-generators within the same power plant. Future work will focus on pilot deployment, calibration of stress weighting factors using long-term operational data, and correlation of stress indicators with inspection and maintenance findings.

Paper 12400 (Germany): Digital Twin Implementations for Subsystems of Turbine Generators and Synchronous Compensators

The report presents a case study in the development of statistical learning models for the monitoring and assessment of operational parameters of generators. This case study investigates the temperature rise of the stator core end packets (step iron) during on-load operation.

The choice of operational parameters, statistical model, and selection of operational training and test data from 15 machines of various frame types and ratings is explained, and the results presented. These models are used to identify deviations from expected behaviour and can help maintenance planners and domain experts by guiding them to machines and operational periods where their expertise is needed for further assessment.

Compared to conventional monitoring or predictive maintenance techniques this data-driven approach seeks to identify indicators of potential issues or maintenance requirements well in advance of traditional threshold-based methods.

The paper proposes future improvements in terms of data selection (e.g. steady-state values) and considering prior operating conditions and temperatures (pre-steady-state heating) to minimise detected anomalies specifically low or no-load and transient load conditions.

Paper 12598 (Brazil) [NGN]: Vibration Severity Criteria Development for MEMS-Enabled Data-Driven Condition Monitoring of Electric Motors

This study proposes a new empirical framework for vibration severity standards specifically tailored for Micro-Electromechanical Systems (MEMS) sensors, increasingly used as alternatives to piezoelectric technology.

ISO 20816-3 currently serves as the industry benchmark for vibration severity of motors, primarily utilizing RMS velocity to assess machine health. According to the paper, the threshold values were calibrated based on the physical characteristics of piezoelectric sensors, monitoring legacy machines. Applying these broad, generalized limits directly can lead to false positives or missed high frequency impacts, which are more accurately detected via direct, unfiltered derived metrics such as RMS and Peak-to-Peak acceleration.

The primary objective of the methodology described in the paper is to derive statistically significant vibration severity thresholds for contemporary vibration sensors placed on three-phase induction motors by analysing a large population-wide dataset. By leveraging a dataset of measured vibration levels from a large fleet of machines (49,320 industrial motors, <300 kW) of different speeds and powers, the research provides population-derived thresholds for three primary metrics; “Velocity RMS”, “Acceleration RMS”, and “Peak-to-Peak acceleration” across nine distinct operational categories based on power (low, medium, high), and speed (low, medium, high). These severity thresholds allow for the simultaneous detection of structural issues and high-frequency impact phenomena, such as early-stage bearing wear, from the very first measurement.

It is claimed that the derived vibration severity threshold criteria can serve as a basis for immediate, reliable assessment of peer-to-peer relative machine health upon sensor installation before AI training begins thus helping to avoid “baseline poisoning” due to latent faults prior to data collection.

3.1.2 Improved maintenance practices to ensure power supply reliability

Paper 10198 (India): Mechanical degradation of hydro generator stator core: advanced diagnostics, on-site remediation, and engineering insights from a field case

It presents a case study of a hydro generator which required extensive core damage repairs after a major overspeed event. The repair was performed in-situ, resulting in a significant reduction in outage time in comparison to a full core re-stack.

The overspeed event caused the release of a rotor V-block support which subsequently impacted the stator core surface causing damage over about 12% of its surface area including damage to vent ducts. The OEM had recommended a complete replacement, citing 12-month minimum lead time for delivery, installation, and commissioning. Internal assessments however, supported by expert consultations, confirmed the feasibility of in-situ repairs representing savings in cost, availability and lost energy production.

The repair work to the stator core entailed EL-CID testing to localise damaged areas, visual inspection, mechanical removal of damaged material and filling with high-dielectric epoxy resin. Impact damage sustained by some rotor poles were similarly filled using a mixed insulating compound of epoxy resin and mica powder to restore insulation integrity and mechanical stability.

The unit was successfully returned to service under a conservative, enhanced operating and monitoring regime with controlled load ramp rates and operating conditions to minimize mechanical and thermal stresses on the machine.

Paper 10200 (India): Comprehensive analysis of chemical cleaning impact on stator winding hollow conductors and generator cooling water system performance

This paper presents the results of a comprehensive analysis of the possible effects of chemical cleaning of water-cooled stator bars with copper tubes on the integrity of the winding itself and on the generator stator winding cooling water system components.

The study considers the impact of chemical cleaning using EDTA (Ethylene-diamine tetra-acetic acid) with oxidiser hydrogen peroxide (H_2O_2) on generator electrical parameters, mechanical integrity and impact on material on multiple generators with operational lifetimes of over 30 years.

The work provides a definitive validation that EDTA-based chemical cleaning with H_2O_2 oxidizer represents a safe, effective solution for generator cooling system maintenance.

Paper 10757 (Japan): Development of an Ultrasonic Testing Robot for Retaining Rings in Turbine Generators

This paper presents the development of an in-situ inspection robot that employs fully automated ultrasonic testing of generator rotor retaining rings with a dry couplant to detect rotor-related defects caused by stress corrosion cracking without requiring rotor disassembly.

The low-friction dry couplant is used in conjunction with the internal elastomer pad of the probe to allow smooth sliding of the probe between measurement locations, and good contact to the retaining ring surface when load is applied to the probe to enable efficient ultrasonic transmission. Each robot is equipped with two ultrasonic testing units, contributing to reduced inspection time.

This approach significantly reduces inspection time and labour costs while avoiding the introduction of foreign materials associated with the traditionally used wet/oil couplant for the

ultrasonic probes. Unlike liquid couplant, the dry couplant does not contaminate the retaining ring surface or the equipment interior, and post-inspection cleaning is unnecessary.

Paper 10785 (Brazil): Theoretical Review and Precautions on Surge Testing Medium and High Voltage Stators in Fully Assembled Rotating Electrical Machines

The paper examines the physical principles, limitations, and risks associated with surge testing when applied to complete stator windings of medium- and high-voltage rotating electrical machines. It presents an overview of surge testing fundamentals, addressing the physical principles of interturn insulation stress, wave propagation and reflection phenomena, and the factors that fundamentally limit detection sensitivity in fully assembled stator windings.

The work reviews insulation systems, ageing mechanisms, and interturn failure modes, explaining why surge testing is highly reliable for individual coils but fundamentally constrained when extended to complete windings. The differing positions of IEC 60034-15 and IEEE Std 522 in applying the test to fully assembled stators are analysed, clarifying why IEC restricts surge testing to manufacturing stages, while IEEE allows its controlled use for field diagnostics while clearly warning about its limitations.

Paper 10787 (Brazil): Methodology to Estimate the Risk of Vibration Sparking (Spark Erosion)

This paper reviews the slot partial discharge (PD) and vibration sparking (VS) mechanisms in stator windings of large generators.

PD in the slot is generally a very slow-acting deterioration mechanism on mica insulation systems, while VS is a fast deterioration mechanism resulting in service failure in a relatively short time and can occur at any point of the winding, including at the neutral side. VS is generated from repeated interruption of the parasitic stator bar surface currents due to bar/coil vibration.

The lower the surface resistance of the outer corona protection (OCP) layer of the stator bar, the higher is the risk of vibration sparking. On the other hand, if the surface resistance is too high, its function to prevent (slot) partial discharges will be jeopardized. The paper provides a simple risk assessment model for calculating the minimum resistance of the OCP to prevent vibration sparking and presents three examples for different high-speed salient pole machines and concludes that a surface resistance in the range of 1000Ω/□ to 10.000 Ω/□ is quite suitable to prevent vibration sparking and (slot) partial discharges in typical hydrogenerators.

Paper 10802 (Brazil): Analytical Determination of the Maximum Induced Turn Voltage in the Field Winding of Hydro-Generators During Stator Faults – The Turn-to-Turn Test Voltage

Under normal operating conditions, the voltage between the turns of the field winding of a hydrogenerator with salient poles will hardly exceed a few volts and may lead to the wrong and dangerous conclusion that the turn insulation is of no concern. However, under transient conditions (namely, a short circuit at the main leads), it is possible that the voltage across turns, instead of the few volts normally anticipated, could become tens or even hundreds of volts.

The paper presents a rigorous analytical method to calculate the maximum induced turn-to-turn voltage in the field winding of salient-pole hydro-generators during stator short-circuit faults. Calculations are presented for thirteen salient pole machines over the power range from 82 MVA to 945 MVA. The analytical approach presented is validated against finite element simulations for three of the machines.

It recommends that the design of field winding interturn insulation and turn-to-turn test voltages should be evaluated considering the maximum induced voltage between the turns of the field coils during transient phenomena.

Paper 11536 (United Kingdom): Detection of electromagnetic faults (air gap eccentricity, open rotor bars, connection issues) in induction rotating machines with off-line dual imbalance test through stator windings

The paper provides an overview of the problem of measuring the dc resistance of windings and explains the concept of the dual imbalance method which utilises the transient part of the induced signals to quantify information about total asymmetry in the electromagnetic system of an induction machine. Combined with the true DC resistance measurement this method is reported to show promising diagnostics results.

The practical implementation of this proposed measurement method is shown for 4 induction motors of different rated powers (1.5kW up to 90kW) and with different types of simulated faults (air gap eccentricity, broken rotor bars). The results indicate that this method can detect various types of electromagnetic imbalances in induction motors and the presence of faults.

Limited tests were applied to much larger HV motors (630 kW, 3 MW, rated up to 13.8 kV) and the results suggest that the method is applicable to any size of induction machine.

Paper 12055 (Thailand): Mitigation and Prevention of Ground Faults in Water-Cooled Generators: A Case Study of Water Box Failures

This paper presents a case study of a stator ground fault in a large water-cooled generator caused by the combined effects of mechanical vibration and degradation of joint integrity within the stator water-cooling system resulting in water leakage.

The paper focuses on three root causes of the stator bar water leakage problem which occurred on the operating unit: cracks in the water box, defective soldered joints between bars, and excessive vibration in operation. The defects were successfully repaired, and mitigation actions have been proposed to prevent such occurrences in future.

The paper proposes preventative maintenance during scheduled outages including pressure/leak testing of the winding, and visual inspection of soldered joints, and operational monitoring including continuous monitoring of water flow within the stator cooling system and dedicated end-winding vibration sensors.

Paper 12610 (Japan) [NGN]: Practical Detection Method of Stator Core Interlaminar Short Circuit for Turbine Generators

The paper describes the development of a “low flux loop test” to detect sub-surface core defects within the stator cores of turbine generators based on the measurement of induced voltages of axially separated stator core regions.

The method described is generally applicable to generators that have a number of radial ducts in the stator core for ventilation of the cooling medium. These radial ducts in the stator core enables the installation of coils for induced voltage measurement. An excitation coil and voltage-measurement coils are wound on equally spaced stator core packets in the axial direction to perform the test.

The experimental development and qualification of the test method using simulated faults is presented in the context of a theoretical background and experimentally confirms how the induced voltage on a certain length of a stator core decreases as the short circuit length in the

axial direction increases. The paper states that this method seems to be effective for detecting interlaminar short circuits distant from the inner periphery of the stator core.

3.1.3 Extending operational performance and service life of installed base

Paper 10796 (Brazil): Condition-Based Operational Strategy for Life Extension of a Hydro Generator with Stator Ovalization

This paper documents a complex high-risk condition detected in a 200 MW Kaplan unit which exhibited vibration levels consistently higher than its sister unit under identical operating conditions. The observed trend threatened the generator guide bearing integrity and by extension the rotor itself.

Advanced condition-monitoring techniques were used to diagnose the progressive, high-risk failure mechanism through integrated analysis of long-term vibration trends, shaft orbits, lubrication particle data, and historical air-gap measurements. Stator ovalization was identified as the fundamental cause of growing rotor eccentricity and unbalanced magnetic pull (UMP) and highlights a key asset-management challenge whereby small geometric nonconformities at commissioning can evolve into major reliability threats over years of operation. By adjusting bearing clearance and intensifying surveillance, the plant was able to maintain safe operation while preparing for corrective repair.

The paper highlights the limitations of insufficient monitoring infrastructure, particularly the absence of operational air-gap sensors, and emphasizes the need for upgraded diagnostic capabilities.

Paper 10988 (Italy Severe damage to synchronous condensers, caused by lube failure, demand stricter requirements for the oil system

This paper focuses on the lubrication and jacking oil system of synchronous generator and flywheel plants and the learnings from two severe system failures which occurred in recent years. Due to significant damage to the rotor, stator, flywheel, bearings, and auxiliary systems, both plant outages lasted more than twelve months.

The paper details two major events, Case A during a blackout test and Case B during normal operation, where loss of lubrication led to extensive mechanical damage. The damage caused is explained and the mechanical and electrical tests required before reintegration of the damaged components into the plant. Case A required complete replacement of the rotor-flywheel assembly due to extreme deformation and contamination, while Case B involved complex restoration processes, including submerged arc welding and thermal treatments, to recover the generator rotor.

The paper presents the corrective actions implemented by the TSO, including hardware upgrades (additional sensors, improved valves, filtration systems) and software modifications to enhance control logic and alarm management, significantly raising the level of operational safety and minimizing the likelihood of similar future events.

Paper 11339 (Australia): Life Evaluation of Strategic Generator and Condenser Assets

This paper describes a method implemented to analyse the operating, maintenance and condition monitoring regime of generator assets to assess the machine condition and quantify operating integrity, expended life and to postulate a remaining lifetime.

Design data, inspection and test data and operating data is collated chronologically and compiled in an expert system to analyse insulation ageing and the general integrity of the machine. The system identifies ageing and possible failure mechanisms of the stator, rotor, stator core and rotor core and quantifies the likelihood and severity of that failure mechanism and the consequence with respect to the machine reliability. A weighted integrity score is assigned to design and manufacturing quality, operating stress levels, maintenance aspects (including remedial repairs), condition monitoring results and failure modes. The sum of the scores is used to derive the overall health and risk ranking. This permits benchmarking of the machine condition with others in the fleet and against sister machines in the database.

A bathtub spline characteristic is used to estimate the equivalent life as a condition-based proportion of the standard machine life (assumed to be 40 years). Estimated remaining life is the difference between the standard machine life and the equivalent life.

A case study is presented in the paper, and it is stated that the method has been applied to eight other similar synchronous condensers (6 off at 60MVAr and 2 off at 35MVAr) and a turbo alternator 280MVA as well as other strategic induction motors in the mining industry.

Paper 12237 (Switzerland): Stator Insulation Performance: Six Decades of Experience

This paper presents a fleet-based evaluation of dielectric dissipation factor (tan δ) and capacitance measurements obtained from more than 85 hydrogenerator stator windings over nearly six decades of operation. In total, 610 offline in-situ measurements were analysed, encompassing machines commissioned between 1957 and the present and covering both thermoplastic (asphalt- and shellac-based) and thermoset (epoxy-based) insulation systems.

Tan δ represents a global insulation parameter that integrates conduction, polarization, and discharge-related losses across the entire winding making it particularly suitable for long-term condition monitoring and aging assessment of stator windings under field conditions. A trend-based evaluation has been used as an indicator of insulation aging in hydrogenerators of different designs, ages, and service histories rather than reliance on absolute threshold values.

The analysis presented indicate that older thermoplastic insulation systems generally exhibit higher absolute tan δ and capacitance values than modern thermoset designs. These differences are primarily attributed to material properties and manufacturing processes rather than in-service ageing. Detailed evaluation of thermoset insulation systems, excluding isolated production- and quality-related anomalies, identify no statistically significant long-term increase in tan $\delta_{1.0}U_n$ on most service-aged stator windings.

The results indicate that, when combined with regular diagnostic testing, visual inspections, and condition-based maintenance, both thermoplastic and thermoset stator insulation systems can remain in reliable operation well beyond their nominal design lifetime.

Paper 12238 (Switzerland): Index-Based Fleet Management for Hydro Generators

The paper presents a new fleet-wide condition index methodology designed to alleviate inconsistencies and expert-dependent subjectivity in the interpretation of machine condition diagnostics. The method applies rigorous, criteria-based scoring across 29 diagnostic and operational parameters, combined with confidence weighting and statistical aggregation to assign a condition index that transforms diagnostic data, operational context, and visual information into a standardized, reproducible, and quantitative indicator. The diagnostic and operational parameters considered include the results from visual inspection, mechanical behaviour, machine history and electrical diagnostic measurements on the stator and rotor windings.

A case study of three 4.25 kV / 9.5 MVA hydrogenerators is presented together with a sensitivity analysis of the condition index to confidence, age weighting, and diagnostic scope. A statistical end-of-life analysis is presented for one of these units.

The approach enables statistically grounded condition evaluation, consistent comparison of units and fleets, and transparent assessment of maintenance effectiveness. The paper reports that the index has been applied to fleets exceeding 70 hydrogenerators and has demonstrated its usefulness for both operational and strategic asset management.

Paper 12361 (South Africa): Seal oil ingress in large turbo generators: A South African utility perspective

This paper presents the results of a study which has investigated the various causes of seal oil ingress events in hydrogen/water-cooled generators based on experience from field inspections, procedural audits, and laboratory analysis of seal oil samples from multiple generating units.

The paper presents two case studies; A, a unit which suffered a single significant seal oil ingress event resulting in oil contamination of the generator components, and B, a unit which experienced smaller but repeated seal oil ingress incidents over several years. The causes of seal oil ingress events are discussed and the potential impact of the resulting rotor and stator contamination assessed.

The paper concludes that there is no need for new or innovative technology to resolve the issue, rather compliance with existing guidance would be sufficient and emphasizes the need for proper training. The theme through the paper is that the perception by the plant operators can be misaligned with technical risks posed by poor control of the seal oil systems.

Mitigation actions have therefore been taken to minimise the occurrence of seal oil ingress through improved operator training and interlocks to prevent seal oil system activation in the absence of positive pressure in the generator frame.

Paper 12630 (China) [NGN]: An Analysis of Long-Term Operation and Maintenance Characteristics of Air-Cooled and Evaporative-Cooled Hydrogenerators at Lijiaxia Hydropower Station

This paper statistically analyses over twenty years of operational and maintenance data from air-cooled and evaporative-cooled hydrogenerators at Lijiaxia Hydropower Station, a facility designated for peak shaving and frequency regulation in the Northwest China Power Grid.

It is important to note that the evaporative-cooled hydrogenerators in the analysis are designed with direct water cooling of the stator winding rather than indirect air-cooling used in the traditional air-cooled generators.

The authors present well-constructed tables describing the operational conditions of the diverse generators during summer and winter. Hydrogenerators experience continuous, significant load-cycling transients (114–162 cycles/month) across a 400-MW output range.

The conclusion states that two decades of rigorous operation under broad load-regulation cycles demonstrate that evaporative-cooled technology significantly enhances the structural reliability of hydrogenerator stators. Furthermore, evaporative-cooled hydrogenerators require markedly fewer major overhauls than their traditional air-cooled counterparts, translating to substantially lower lifecycle maintenance costs.

3.2 PS3 Discussion

An important aspect of the power generation landscape is the proper management of existing assets to ensure reliable operation, optimised availability and maximise service life while controlling the operational and maintenance costs.

The energy transition to renewable but more variable energy sources is putting increased burden on existing power generation equipment, associated auxiliaries and motors to operate under much more flexible and cyclic operational duty and rapidly changing load profiles. Owners are continuing to review their operational and maintenance practices to ensure that their equipment can reliably meet these increased demands.

Maintenance practices, test methods, parameter monitoring and diagnostics, and machine condition assessment are therefore continually being reviewed and are evolving to enhance the effective management of existing assets whilst minimising the need for extensive, dedicated domain expertise. AI-based methods are being increasingly deployed to analyse and model historical data.

The availability of more cost effective sensors and rapidly increasing computing power is allowing more automated collection and assessment of high volumes of operational data. This data is being used to detect and investigate existing and developing problems [10789, 10797, 10801] and monitor machine design and component performance [10792, 12630].

Data analysis techniques are being improved to more effectively and automatically screen and trend operating parameters and interpret them into meaningful condition indicators without the need for continuous assessment by domain experts, e.g. partial discharge analysis using VHF comparator arrays [11971] or machine learning and statistical analysis techniques [11352].

Traditional fixed alarm and limit values for critical parameters may be replaced by data driven statistical operating envelopes to allow earlier detection of abnormal operation across varying duties, load regimes and environmental conditions [12598]. Ultimately digital twins are envisaged to predict expected parameter values with tolerance ranges based on actual operating conditions to compare against measured operational data in real time. An essential step in developing a digital twin is creating the algorithms or data models that can return reliable on-load parameter estimations [11790, 12400]. Challenges exist in allowing for transient variations in load conditions, time delays in parameter changes, and the effect of previous load conditions on the instantaneous values. Periods of steady-state load and environmental conditions sufficient to allow parameter readings to stabilise can no longer be assumed.

Trends in operating, test and maintenance data for specific aspects of the machines are being scored, weighted, integrity checked and compiled into health indicators and health indices for particular components and even the complete machine [10821, 12331]. These derived health indicators are being used to make informed decisions concerning equipment maintenance, repair or replacement and even qualitative judgements on remaining life. Such assessments can be purely data driven using AI models or combined with physical models to enhance analysis. The challenge with data driven systems is how to deal with operating conditions that are outside the range of the training data used and ensuring that the training data contains no latent faults.

The increasing availability of historical data also facilitates the identification, quantification and understanding of common ageing mechanisms [12237].

Maintenance practices [10200, 12055] are being improved and test techniques adapted [10757, 10785, 10787, 10802, 11536, 12610] to provide a better understanding and mitigation of equipment failure modes. This facilitates on-site repair options to be considered to extend service life rather than carry out immediate replacement [10198].

Lessons learned from past or recurring problems are being addressed by improved operation safeguards and procedures [10988, 12361].

The combined experience of all the above is being used to create machine health indices for more structured fleet management and service life assessment/extension [10796, 11339, 12238].

3.3 PS3 Questions

[Q3.01]: Full digital twins will require accurate and reliable parameter predictions to made in real time based on the actual operating conditions of the machine. Since load profiles are becoming increasingly variable, the transient effects of short term load changes, delays in parameter response (e.g. temperature and vibration levels) and the impact of previous load conditions need to be assessed. How can this be addressed in future digital twin models; can it be purely data-driven or will physical electro-thermal modelling also need to be integrated?

[Q3.02]: In addition to frequent, but normal transient conditions raised in Q3.01, models will need to effectively assess/predict parameters for rare/unusual abnormal operating conditions potentially outside the range of standard historical data used for model training. How can rare load excursions be effectively handled without raising false alarms/trips?

[Q3.03]: It has been presented that some units have been commissioned already with faults present that were not detected during normal commissioning checks/tests. Data-driven models adapting to unit specific operating data will consider this as normal. One paper termed this “AI data poisoning”. Is this considered generally unlikely on new machines, or, if not, do commissioning validation threshold/criteria need to be more rigidly enforced/reviewed?

[Q3.04]: Global insulation condition parameters (tan δ, capacitance) have been described as being good indicators of long term insulation system performance, whereas other condition monitoring parameters (e.g. partial discharge) reveal shorter term or localised problems. How are these two assessments being combined when considering when, and to what extent, to intervene for inspection, repair or rewind?

[Q3.05]: Several papers have described the development and use of component or machine health indices to give a more structured and fleet-wide method to assess independent assets and prioritise maintenance, repair and replacement decisions. The various methods have some similarities but vary on the parameters/information and weightings and integrity factors used in the approach. Is there a need for a more common approach via the development of international standards / guidelines?

[Q3.06]: One paper proposes data-driven vibration limits instead of the fixed values assigned in ISO20186-3 for machine vibration and suggests values for 9 categories of machines based on speed and power ranges. Is this level of refinement of acceptable operating parameters practical, and are there other parameters (electrical, thermal or mechanical) which should also be re-evaluated based on a data-driven approach?

[Q3.07]: So far data driven condition monitoring has been used to give indicators or guidelines for the need for potential inspection, maintenance or repair. Protection trip settings presumably still use mainly fixed values based on defined limits or

ratios to what are considered normal expected values. One paper has discussed adaptive capability charts based on multi-factor considerations, but is it foreseen that history adapted values could be used in the future for automated de-loading/trip if imminent machine damage is predicted?

[Q3.08]: How are maintenance practices evolving to address the increase in load shifting/cycling and reduction in operating hours for generation equipment? Is enough being done to maintain more older power stations, sometimes past their original design life?

[Q3.09]: When considering life extension /upgrades for existing plant, are the new operating regimes being sufficiently considered, e.g. generators / synchronous condensers subject to higher levels of grid harmonics; motors retrofitted with VF drives for more flexible/adjustable operation?

[Q3.10]: The contributions provided in response to this Preferential Subject tend to be reactive, i.e., dealing with the consequences imposed by the increased penetration of inverter-based generation and the concomitant changes in grid codes. Are there any examples of generation utilities engaging with these entities to reduce the negative consequences for generation assets?

[Q3.11]: Regarding the application of AI and machine learning methodology applied to condition monitoring, diagnostics and prognostics, is there a correlation between the parameter(s) monitored, e.g., vibration, partial discharge, temperature, etc., and output, i.e., success of the method?

4. Procedure for submitting contributions

Registered delegates can prepare one or several contributions to the Study Committee Group Discussion Meeting (GDM) related to the questions raised in this report.

1. Contributors should upload contributions on the registrations portal – "Contributions to Group Discussion Meetings" section - using your existing account and own credentials before 7th August 2026, for a prior screening and a good organization of the Group Discussion Meeting. Important points:
2. Access to contribution uploading is given only to duly registered delegates.
   - As a consequence, registration to CIGRE Session should be finalized before uploading contribution(s) online.
   - Register now for the Session registrations
   - Contributions uploading will be open at the start of June.
3. Special Reporters will review the prepared contributions (Power point presentation and a written word file per contribution). A guide for contributors as well as templates and sample pages will be available on the Paris Session webpage. Important notice: No commercial names are to be included in the presentation or the written summary (even TSO/DSO names).
4. Any recommendations or changes to the contributions will be provided to the contributors by the Special reporters directly on the Registration platform between 7th of August and 14th of August 2026. Contributors are encouraged to visit their account on the registrations portal to see the result of this review.

5. All contributors with accepted/finalised contributions will be contacted by the Special reporters between 7th of August and 14th of August 2026, to finalize the presentation and receive the instructions regarding the session.
6. Important note:
    - All contributions must be uploaded prior to the Conference in Paris.
    - Last minute changes to the contributions will not be granted.
7. During the GDM the Study Committee Chair may call for spontaneous contributions, which will only be verbal with no slides. All attendees are eligible to make such a contribution. Attendees who provide a spontaneous contribution are allowed to deliver a written contribution which will be included in the Session Proceedings. This text is required to be forwarded within a maximum delay of two weeks after the Study Committee GDM Session (i.e. by **Friday 11th September**) **to the SC Secretary** (Peter.Wiehe@hydro.com.au).
8. It is expected that the questions relevant to the Preferential Subjects will attract many prepared contributions. The number of contributions for each Preferential Subject (PS1, PS2 and PS3) may need to be limited. The selection will be based on relevance, quality and time of submission of the contribution.
9. Please note that the Special Reporters, SC Chair and SC Secretary will be available on **Wednesday 26th August** between **14:00-16:00** in the **SC A1 Poster Session area** at the Palais des Congrès for contributors to handover any final changes to their presentations if necessary or to review any final details of their contribution to the GDM.

Main key dates:

Deadline for acceptance of GDM contributions	**7th August 2026***
SC A1 Poster Session	Wednesday 26th August 2026, 14:00-18:00
SC A1 GDM	Thursday 27th August 2026, 08:45-18:00

***Note** *: Please upload at least 1 week earlier than the acceptance deadline to allow review and possible revision of contributions.*